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APPROACH GUIDANCE SYSTEM
PROTOTYPE COMPUTER PROGRAM DEFINITION

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TRW SYSTEMS

ONE SPACE PARK • REDONDO BEACH, CALIFORNIA

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ABSTRACT

In accordance with Phase I of JPL Contract No. 95136, this report covers the Prototype Computer Program Definition for the mathematical error model of the Approach Guidance System. The Prototype Computer Program Definition presented will simulate the observations to be taken by the Approach Guidance System. A description of the overall program layout and of each subroutine is presented.

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The preparation of this document is the result of the combined efforts of the following members of the TRW Systems Technical Staff:

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NOMENCLATURE

A	Program variable defined in subroutine A
A_1	Wedge angle, nominally $6^{\circ}39'04''$ see Figure 19
A_2	Wedge angle, nominally $10^{\circ}53'23''$ see Figure 19
A_3	Fore prism angle, nominally $32^{\circ}30'$ see Figure 19
A_4	Fore prism angle, nominally $21^{\circ}27'$ see Figure 19
A_5	Fore prism angle, nominally $22^{\circ}06'$ see Figure 19
B	Program variable defined in subroutine D
C	Vehicle rate after issuance of first control pulse
C_p	Program variable used in LIMCYC subroutine which is related to pitch
C_y	Program variable used in LIMCYC subroutine which is related to yaw, also used in subroutine THETA
C_R	Program variable used in LIMCYC subroutine which is related to roll
D	Program variable used in LIMCYC subroutine
D_p	Program variable used in LIMCYC subroutine which is related to pitch
D_R	Program variable used in LIMCYC subroutine which is related to roll
D_y	Program variable used in LIMCYC subroutine which is related to yaw
E	Program variable used in LIMCYC subroutine
I	Program variable used in LIMCYC subroutine which is used for moment of inertia
I_p	Pitch axis moment of inertia
I_R	Roll axis moment of inertia
I_y	Yaw axis moment of inertia
K_n^c, K_n^{c1}	Canopus tracker polynomial coefficients for converting mrad to volts and volts to mrad respectively

NOMENCLATURE (Continued)

K_n^p, K_n^{p1}	Planet tracker polynomial coefficients for converting mrad to volts for the planet diameter readout and volts to mrad respectively
K_n^s, K_n^{s1}	Auxiliary Sun sensor polynomial coefficients for converting mrad to volts and volts to mrad respectively
$N_{\theta\psi}$	Quantized output value for the planet tracker wedge measured cone angle
$N_{\theta\chi}$	Quantized output value for the planet tracker wedge measured cross-cone angle
$N_{\phi p}$	Quantized output value for the auxiliary Sun sensory measured pitch angle
$N_{\phi pM}$	Maximum value for the pitch angle quantization
$N_{\phi R}$	Quantized output value for the Canopus tracker measured roll angle
$N_{\phi RM}$	Maximum value for the roll angle quantization
$N_{\phi t}$	Quantized output value for the planet tracker measured planet diameter angle
$N_{\phi tM}$	Maximum value for the planet diameter angle quantization
$N_{\phi y}$	Quantized output value for the auxiliary Sun sensors measured yaw angle
$N_{\phi yM}$	Maximum value for the yaw angle quantization
P	Program variable in LIMCYC subroutine
$P_{a,b,c}$	Vector components used in computing cone and clock angles in subroutine ANGLE
P_T	Line-of-sight vector in planet tracker coordinate system
R	Decimal equivalent of percentage of limit cycle completed since end of last limit cycle
$R_{i,F}$	Index of refraction for fore prism (1.517) see Figure 19
$R_{i,G}$	Index of refraction for gas (1.000417) see Figure 19
$R_{i,s}$	Index of refraction for space (1.0) see Figure 19

NOMENCLATURE (Continued)

$R_{i,1}$	Index of refraction for wedge (1.649) see Figure 19
$R_{i,2}$	Index of refraction for wedge (1.517) see Figure 19
$R_{p,y,R}$	Vehicle rate at issuance of first control pulse in pitch, yaw, and roll, respectively
$R_{1,2,3}$	Vector components defined in subroutine AGOPT
$S_{p,y,R}$	Program variables used in subroutine PYRTRA
t	Time
t_{ab}	Time between the second and third pulse
t_{ba}	Time between the first and second pulse
t_f	Time of issuance of next control pulse
t_{min}	Minimum on time
t_n	Time for undisturbed limit cycle
t_{new}	Time for determining limit cycle attitude
t_o	Initial time
$t_{o,p,y,R}$	Initial time for pitch, yaw and roll, respectively
$t_{p,y,R_{min}}$	Minimum on time in pitch, yaw and roll, respectively
t_T	Total duration of two pulse limit cycle
$t_{T,p,y,R}$	Time preceding the first control pulse in pitch, yaw and roll, respectively
T	Program variable used in subroutine LIMCYC for initiating and terminating attitude determination and for temperature designation
T_c	Program variable used in subroutine LIMCYC
T_D	Program variable used in subroutine LIMCYC
T_t	Temperature at current time
T_{t-1}	Temperature at the previous time
T_1	Rotation matrix from body-fixed planet tracker coordinates to body-fixed spacecraft coordinates

NOMENCLATURE (Continued)

T_2	Rotation matrix from body-fixed spacecraft coordinates to celestially-fixed spacecraft coordinates
T_3	Rotation matrix from celestially-fixed spacecraft coordinates to the abc coordinates
U	Variable used in subroutine E
W	Variable used in subroutine E for determining sign of vehicle rate
X	Variable used in subroutine AGOPT to designate wedge cone angle
Y	Variable used in subroutine AGOPT to designate cross-cone angle
Z	Variable used in subroutine E
α, α_t	Clock angle
α_b^s	Auxiliary Sun sensor temperature drift coefficient
α_{bN}	Canopus tracker null plane misalignment
$\alpha_{b\psi}, \alpha_{b\chi}$	Rotation angle uncertainty in cone and cross-cone angles, respectively
α_c^s	Auxiliary Sun sensor electrical null drift coefficient
$\alpha_{c\psi}, \alpha_{c\chi}$	Angular misalignments of the cone axis and cross-cone axis, respectively
α_d	Planet tracker combined mechanical and electrical thermal drift coefficient
α_d^s	Auxiliary Sun sensor thermal alignment electrical drift coefficient
α_{dN}^c	Canopus tracker nominal combined mechanical and electrical thermal drift coefficient
α_{f2}	Planet tracker thermal drift coefficient-power supply voltage variations
α_{g2}	Planet tracker thermal drift coefficient-power supply frequency variations
α_i	Dynamic scale-factor error

NOMENCLATURE (Continued)

α_k	Scale factor relating angular effect error to planet angular diameter
α_n	Planet clock angle
α_o	Planet tracker null axis clock angle
$\alpha_{\theta\psi 2}$, $\alpha_{\theta\chi 2}$	Planet tracker thermal coefficient of the angular offset error due to optical gimbal refractive index drift – cone angle and cross-cone angle
$\alpha_{\psi 2}$, $\alpha_{\chi 2}$	Planet tracker thermal coefficient of the gimbal encoder coupling – cone angle and cross-cone angle
β, β_t	Cone angle
β_c	Canopus cone angle
β_{co}	Canopus tracker null axis cone angle
β_o	Planet tracker null axis cone angle
γ	X axis clock angle
$\Delta\theta_{p, y, R}$	Variables used in subroutine ANGLE
$\Delta\theta_{\psi_o}$, $\Delta\theta_{\chi_o}$	Planet tracker nominal cone angle and cross-cone angle encoder resolution
$\Delta\phi_{p_o}$	Auxiliary Sun sensor pitch angle nominal step width quantization resolution
$\Delta\phi_{R_o}$	Canopus tracker roll angle nominal step width quantization resolution
$\Delta\phi_{t_o}$	Planet tracker planet diameter angle nominal step width quantization resolution
$\Delta\phi_{y_o}$	Auxiliary Sun sensor yaw angle nominal step width quantization resolution
ϵ	Used to define errors associated with the already defined error sources

NOMENCLATURE (Continued)

$\theta_{a,b}$	
$\theta_{a,b}$	Variables used in subroutines A, B, C, and D
$\theta_{am,bm}$	
$\theta(o)_{p,y,R}$	Pitch, yaw, roll initial angles in spacecraft body axis
$\dot{\theta}(o)_{p,y,R}$	Pitch, yaw, roll initial angular rates in spacecraft body axis
$\theta_{p,y,R}$	Pitch, yaw, and roll angles in spacecraft body axis
$\dot{\theta}_{p,y,R}$	Pitch, yaw, roll angular rates in spacecraft body axis
$\hat{\theta}_{p,y,R}$	Nominal pitch, yaw, and roll angles in spacecraft body axis
θ_{p_n, y_n, R_n}	Pitch, yaw, roll variables used in subroutine LIMCYC
θ_{R_o}	Variable used in subroutine THETA
θ_t	Variables used in subroutine E
$\dot{\theta}_1$	
θ_{ψ_m}	Maximum planet tracker ψ wedge angle
θ_{χ_m}	Maximum planet tracker χ wedge angle
λ_D	Variables used in subroutine LIMCYC
λ_C	
σ_a^c	Canopus tracker initial null axis misalignment standard deviation
σ_a^s	Auxiliary Sun sensor initial null axis misalignment standard deviation
σ_{A1}	Wedge angle standard deviation for A1

NOMENCLATURE (Continued)

σ_{A2}	Wedge angle standard deviation for A2
σ_{A3}	Fore prism angle standard deviation for A3
σ_{A4}	Fore prism angle standard deviation for A4
σ_{A5}	Fore prism angle standard deviation for A5
σ_b^c	Canopus tracker null plane misalignment standard deviation
σ_d^c	Canopus tracker electrical thermal alignment drift standard deviation
σ_d^s	Auxiliary Sun sensor accumulated null axis drift due to detector aging standard deviation
σ_e^c	Canopus tracker mechanical thermal alignment drift standard deviation
σ_f^c	Canopus tracker null drift due to power supply voltage standard deviation
σ_f^s	Auxiliary Sun sensor drift due to power supply voltage standard deviation
σ_{f1}	Planet tracker power supply voltage variation standard deviation
σ_{f2}	Planet tracker thermal drift coefficient-power supply voltage standard deviation
σ_g^c	Canopus tracker null drift due to power supply frequency standard deviation
σ_{g1}	Planet tracker power supply frequency variation standard deviation
$\sigma_{i,F}$	Index of refraction standard deviation for $R_{i,F}$
$\sigma_{i,G}$	Index of refraction standard deviation for $R_{i,G}$
$\sigma_{i,s}$	Index of refraction standard deviation for $R_{i,s}$
$\sigma_{i,1}$	Index of refraction standard deviation for $R_{i,1}$
$\sigma_{i,2}$	Index of refraction standard deviation for $R_{i,2}$
σ_j^c	Canopus tracker noise standard deviation

σ_n^c	Canopus tracker cone-to-roll cross coupling calibration standard deviation
σ_T	Temperature standard deviation
$\sigma_{\alpha b}^c$	Canopus tracker rotation angle standard deviation
$\sigma_{\alpha b}^s$	Auxiliary Sun sensor temperature drift coefficient standard deviation
$\sigma_{\alpha b\psi}$, $\sigma_{\alpha b\chi}$	Planet tracker cone angle and cross-cone angle rotation standard deviation
$\sigma_{\alpha c}$	Canopus tracker null - plane misalignment standard deviation
$\sigma_{\alpha c}^s$	Auxiliary Sun sensor electrical null drift coefficient standard deviation
$\sigma_{\alpha c\psi}$, $\sigma_{\alpha c\chi}$	Planet tracker cone angle and cross-cone angle misalignment standard deviation
$\sigma_{\alpha d}^c$	Canopus tracker combined mechanical and electrical drift coefficient standard deviation
$\sigma_{\alpha g2}$	Planet tracker thermal drift coefficient-power supply frequency standard deviation
$\sigma_{\alpha h}^c$	Canopus tracker cone-to-roll cross-coupling calibration standard deviation
$\sigma_{\alpha K}$	Planet tracker scale factor relating angular offset to planet angular diameter standard deviation
$\sigma_{\alpha\theta\chi 2}$	Planet tracker cross-cone gimbal angle encoder thermal coefficient standard deviation
$\sigma_{\alpha\theta\psi 2}$	Planet tracker cone gimbal angle encoder thermal coefficient standard deviation
$\sigma_{\alpha\chi 2}$	Planet tracker cross-cone angle thermal drift coefficient standard deviation
$\sigma_{\alpha\psi 2}$	Planet tracker cone angle thermal drift coefficient standard deviation
$\sigma_{\Delta\theta}$	Auxiliary Sun sensor pitch and yaw angle step width quantization resolution standard deviation
$\sigma_{\Delta\theta D}$	Planet tracker decoder readout resolution

NOMENCLATURE (Continued)

$\sigma_{\Delta\phi}$	Auxiliary Sun sensor pitch and yaw angle step width quantization resolution standard deviation
$\sigma_{\Delta\phi_o}$	Planet tracker planet diameter angle step width quantization resolution standard deviation
$\sigma_{\Delta\phi_{pD}}$	Auxiliary Sun sensor pitch decoder readout resolution
$\sigma_{\Delta\phi_R}$	Canopus tracker roll quantization standard deviation
$\sigma_{\Delta\phi_{RD}}$	Canopus tracker decoder readout resolution
$\sigma_{\Delta\phi_{tD}}$	Planet tracker planet diameter angle decoder readout resolution
$\sigma_{\Delta\phi_{yD}}$	Auxiliary Sun sensor yaw decoder readout resolution
σ_{χ_1}	Planet tracker cross-cone angle angular offset bias standard deviation
$\sigma_{\psi m}$, $\sigma_{\chi m}$	Planet tracker cone angle and cross-cone angle ideal transfer function scale factor standard deviation
$\sigma_{\psi 1}$	Planet tracker cone angle angular offset bias standard deviation
ϕ_{pVM}	Maximum auxiliary Sun sensors pitch angle readout
$\phi_{p,y,R}$	Nominal pitch, yaw, and roll measured by the Auxiliary Sun sensors and Canopus tracker in mrad
$\phi_{pv,yv,Rv}$	Same as $\phi_{p,y,R}$ except the units are volts
ϕ_{RVM}	Maximum Canopus tracker roll angle readout
$\phi(t)$	Planet angular diameter as a function of time
ϕ_{tVM}	Maximum planet tracker planet diameter angle readout
ϕ_{yVM}	Maximum auxiliary Sun sensors yaw angle readout
$\Phi(t)$	Canopus cone angle deflection cone setting

NOMENCLATURE (Concluded)

χ	Planet tracker line-of-sight cross-cone angle
$\dot{\chi}$	Planet tracker line-of-sight cross-cone angle rate
$\hat{\chi}$	Noised planet tracker line-of-sight cross-cone angle
χ_m	Planet tracker cross-cone ideal transfer function scale factor
χ_t'	Current planet tracker line-of-sight cross-cone angle
χ_{t-1}	Past planet tracker line-of-sight cross-cone angle
ψ	Planet tracker line-of-sight cone angle
$\dot{\psi}$	Planet tracker line-of-sight cone angle rate
$\hat{\psi}$	Noised planet tracker line-of-sight cone angle
ψ_m	Planet tracker cone ideal transfer function scale factor
ψ_t	Current planet tracker line-of-sight cone angle
ψ_{t-1}	Past planet tracker line-of-sight cone angle
END	Trajectory tape time at which the simulation segment will end
INLIST	A list of numbers which denote the subscripts of the words to be used from the trajectory record as input
KOMAC	Designates as to whether an auxiliary tape should be generated (0 do not generate and 1 generate)
LISTOB	Designates printed output frequency for each trajectory segment
LRAND	Random number start point
MAXCYC	Number of cycles through the trajectory for this run
NENTRY	Number of entries per record on the auxiliary tape
NLIST	Number of words from the trajectory record to be used as input
NWDS	Number of words per auxiliary trajectory record
NWORDS	Number of words per input trajectory record
SPACE	Time increment spacing between observations

1. INTRODUCTION AND SUMMARY

This report for the Prototype Computer Program Definition for the Approach Guidance System is based on the mathematical error models presented in Reference 1 and is submitted in accordance with Phase I of JPL Contract No. 951936. The report describes the formulation and grouping of subroutines required to produce simulated observation data for the Approach Guidance System. A description of the errors and their corresponding statistical distribution is presented in Reference 1.

Approval by JPL of this document will constitute acceptance of the Prototype Computer Program Definition of the Approach Guidance System.

2. PROTOTYPE COMPUTER PROGRAM PURPOSE AND DESCRIPTION

The purpose of the Prototype Computer Program is to simulate the Approach Guidance System measurements. The measurements will be used to estimate the spacecraft's orbit. A description of the Approach Guidance System and the sensors for establishing a celestial coordinate reference is presented in Figure 1. The quasi-inertial celestial reference system illustrated in Figure 1 is established through Sun sensors that lock on the Sun and a Canopus tracker that locks on the star Canopus. The LOS angle measurements are obtained through a planet tracker that locks on and tracks the planet.

The Approach Guidance System provides five angles. Two angles define the LOS direction to the planet relative to the spacecraft's coordinate system. The other three angles define the pitch, yaw, and roll positions due to the limit cycle motion of the spacecraft coordinate system with respect to a coordinate system defined by the current directions from the spacecraft to the Sun and Canopus. The proper combination of these five angles yields the direction from the spacecraft to the planet with respect to the Sun and Canopus.

2.1 PROTOTYPE COMPUTER PROGRAM DEFINITION

The overall information flow for the Prototype Computer Program (PCP) is presented in Figure 1. The PCP as shown has the necessary logic to process the input trajectory tape to produce simulated Approach Guidance System observation data for a selected segment of the input trajectory tape. Provisions for possible future applications of the PCP's capability to Monte Carlo have been incorporated. The volume of information required from the trajectory tape for each time interval is relatively small (Table 1) but dispersed throughout each record. To minimize running time, especially when one wishes to Monte Carlo, an option has been provided to generate an auxiliary tape containing only necessary information extracted from the original trajectory tape. The user has the option of selecting either the original trajectory tape or the condensed version trajectory tape. The capability to linearly interpolate among trajectory data points stored on the trajectory tape has been included and provides the potentiality of selecting desired observation time

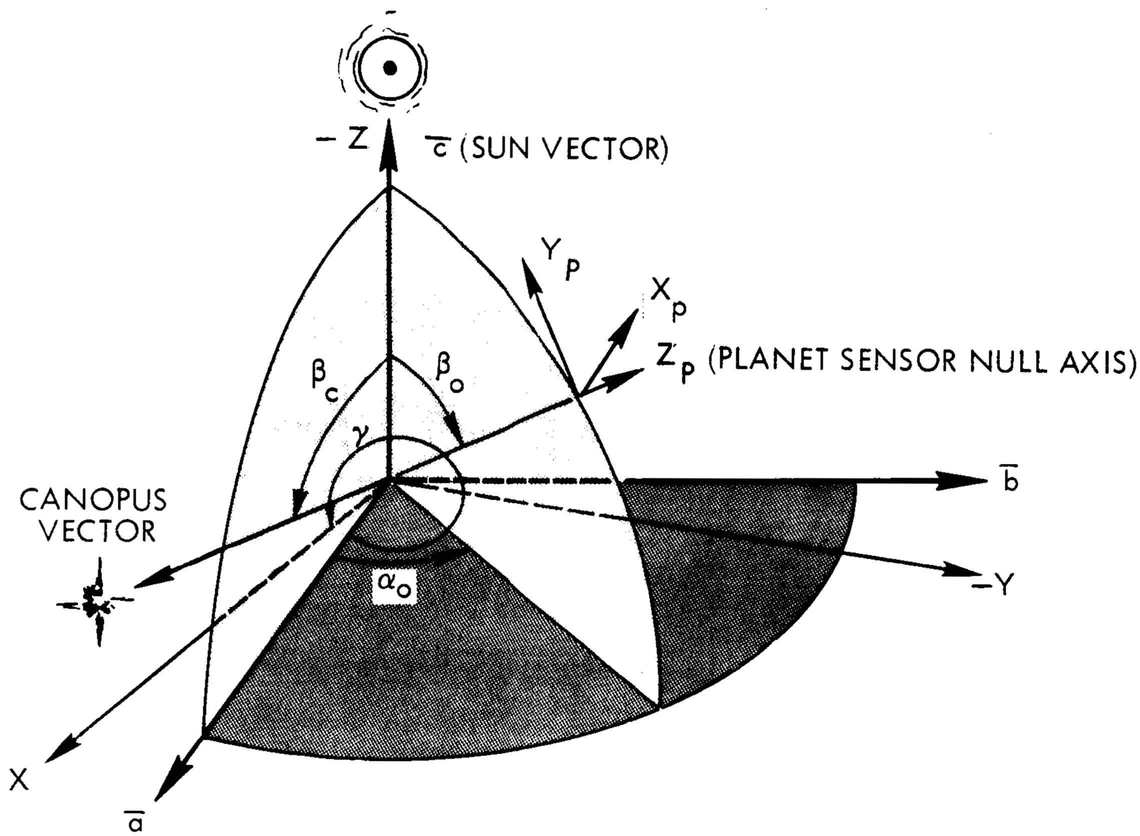


Figure 1. Celestial and Planet Tracker Reference Coordinate System

Table 1. Information Required from the Trajectory Tape

Time (t), sec
Planet-Probe-Sun Angle (β_n), deg
Angular semidiameter of planet ($\phi(t)$), deg
Canopus-Probe-Sun angle (β_c), deg
Canopus clock angle earth center (α_E^c), deg
Target clock angle earth center (α_E^T), deg

increments. Since the interpolation is linear, the linear assumptions should not be violated when selecting time intervals on the trajectory tape.

In the original trajectory tape mode the tape is initially positioned at a specified trajectory starting time, which becomes the first record to be processed. Record processing involves four basic steps:

a. Extracting required trajectory data and sorting it into proper computer areas

b. Generating the observations called for by the simulation

c. Storing the observations on tape

d. Printing the observations at prespecified time intervals

Each trajectory record (time point) is processed in this manner until the trajectory time is equal to, or greater than, a specified end time.

In the auxiliary trajectory tape mode the original trajectory tape is positioned through input start and end times. The original trajectory tape is read and only information required to compute the observation is stored sequentially in a temporary storage area. When the area is filled, information is transferred in block form onto the auxiliary trajectory tape. After transferring the trajectory information for the required time interval, the program returns to the primary mode and processes the auxiliary tape using the four basic steps described above.

Program termination is effected by a counter that advances on completion of each trajectory time segment (e.g., 10 days). When another cycle through the trajectory time segment is called, the program re-initializes the processing loop according to the mode of operations under which it has been executed. Both modes, either original or auxiliary, call the initialization routine and compute all specified parameters.

The general information flow for the PCP is presented in Figure 2; and the linear interpolation subroutine, REDTAP, is illustrated in Figure 3. Subroutine OBS contains all routines required to simulate the Approach Guidance System observation data.

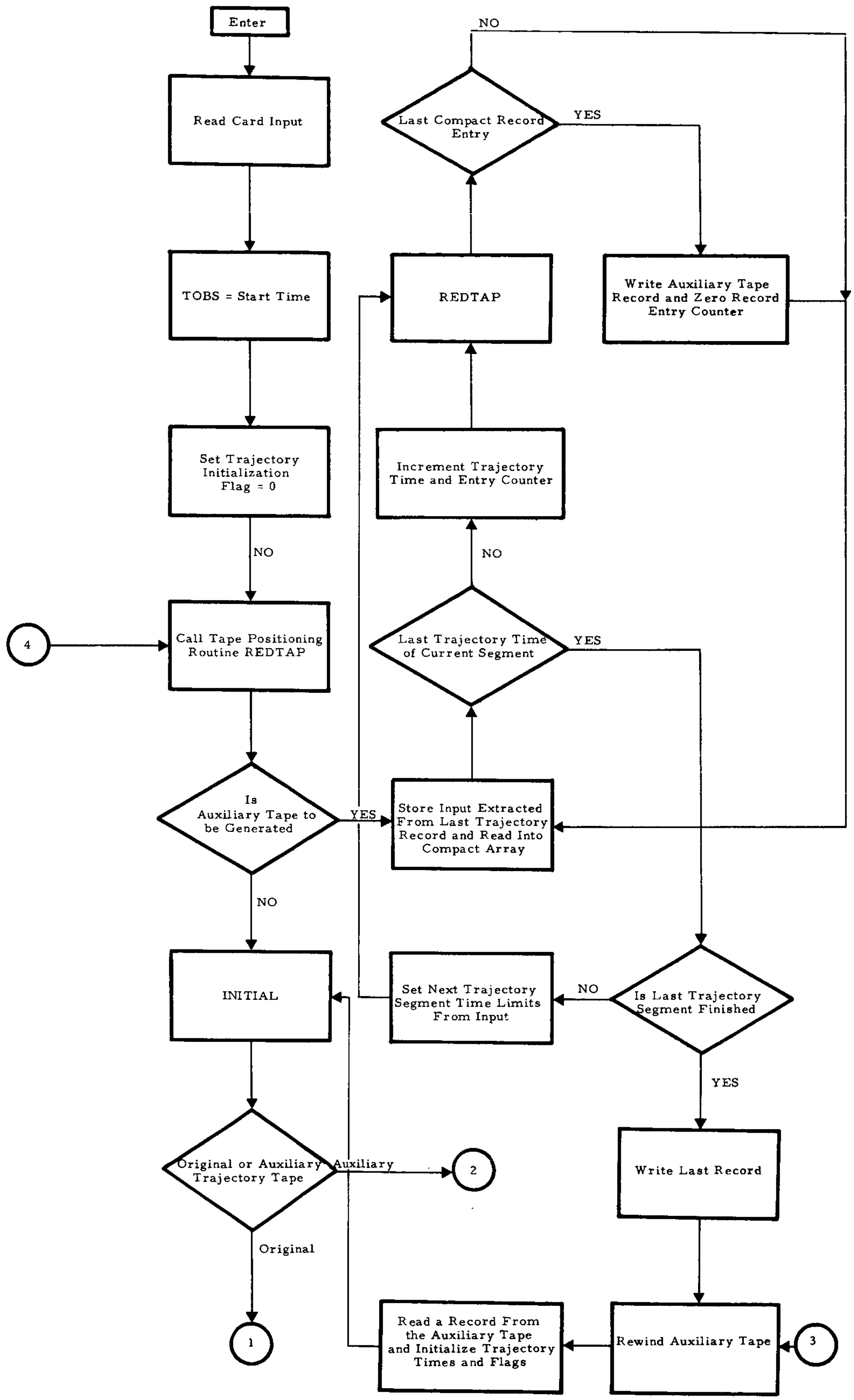


Figure 2. Approach Guidance Prototype Computer Program Flow Diagram

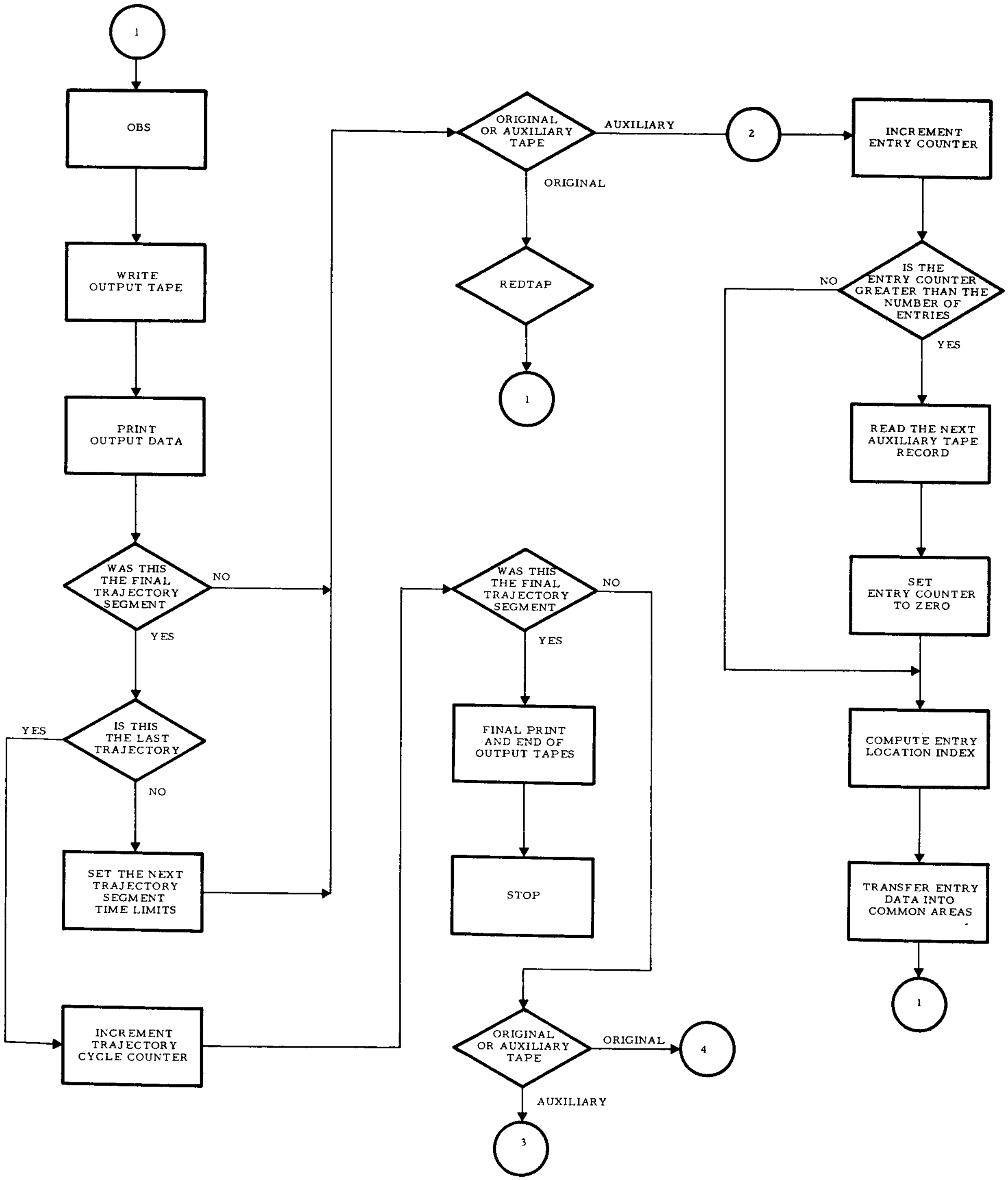


Figure 2. Approach Guidance Prototype Computer Program Flow Diagram (Concluded)

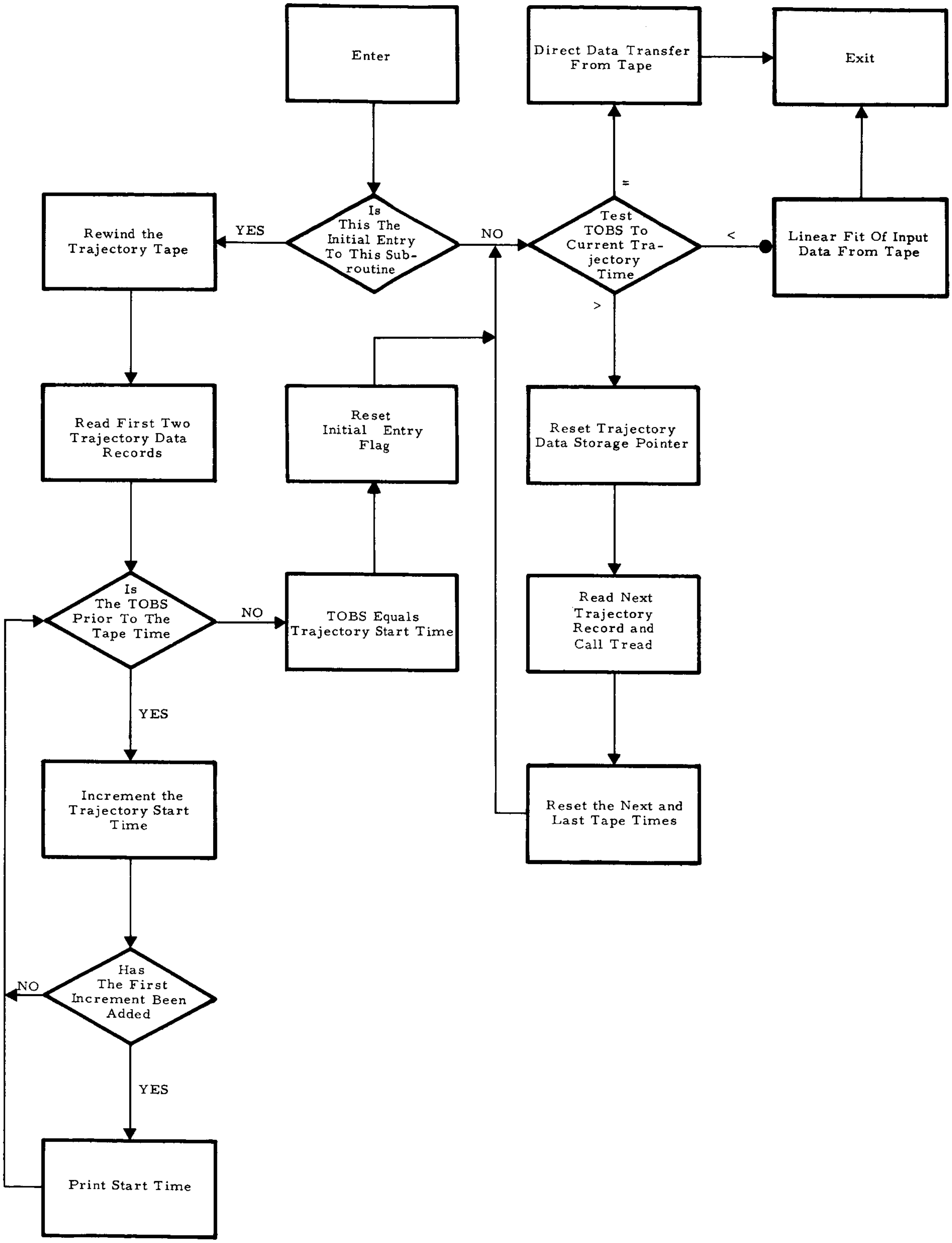


Figure 3. Subroutine REDTAP

2.1.1 Input/Output Description

The information required to produce simulated observation data of the Approach Guidance System consists of a trajectory tape and card input data. The trajectory tape contains the necessary nominal spacecraft trajectory information as a function of time. The spacecraft information that is required is listed in Table 1. The card input data consist of all error sources, all nominal input values, and program control input data (see Table 3). The output values are found in Table 3.

2.1.2 Program Control Input Data

Control of the program is maintained through a set of variables that are presented in Table 2 and defined in the nomenclature. These variables will be input under the namelist name INPUT. The variables consist of the following: START, LRAND, KOMPAC, MAXCYC, END, SPACE, NLIST, INLIST, NENTRY, NWDS, LISTOB, WRITOB, and NWORDS.

2.1.3 Subroutine INITIAL

The computation of all bias errors and various parameters that are representative of a mission are computed in subroutine INITIAL (see Figure 4). The bias errors computed do not change during a mission, but vary from mission to mission. Parameters that are selected for ground processing are selected prior to a mission; hence, they vary only from mission to mission. To facilitate the identification of the bias errors and the parameters computed, they have been grouped into four blocks:

a. Canopus related values

b. Auxiliary Sun sensors' related values

c. Planet tracker optical system related values

d. Planet tracker electronics related values

2.1.3.1 Subroutine RN2S

Independent random numbers, normally distributed with mean zero and standard deviation unity, are generated in subroutine RN2S. The method used produces normal deviates in independent pairs by the formulas

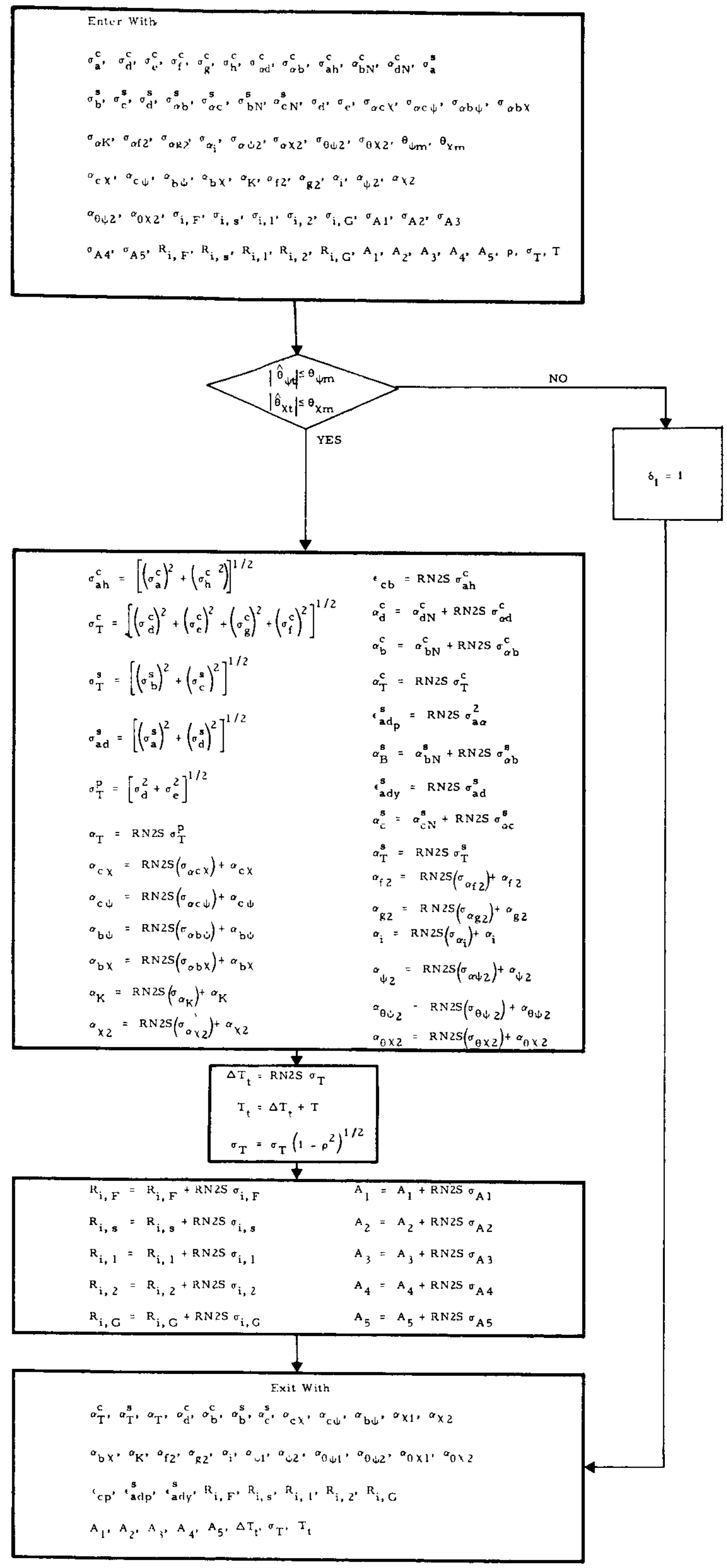


Figure 4. Subroutine INITIAL

Table 2. Input Values

σ_a^c	σ_b^s	$\sigma_{i,1}$	$\sigma_{\alpha\chi 2}$	α_{g2}	$\theta_{\psi m}$	A_5	IFP
σ_d^c	σ_c^s	$\sigma_{i,2}$	$\sigma_{\theta\psi 2}$	α_i	$\theta\chi_m$	I_p	START
σ_e^c	σ_d^s	σ_{A1}	$\sigma_{\theta\chi 2}$	α_K	$\dot{\theta}_p$	I_R	LRAND
σ_f^c	σ_f^s	σ_{A2}	$\sigma_{\psi m}$	$\alpha_{\psi 2}$	$\dot{\theta}_y$	I_y	KIMPAC
σ_g^c	$\sigma_{\alpha b}^s$	σ_{A3}	$\sigma_{\chi m}$	$\alpha_{\chi 2}$	$\dot{\theta}_R$	D_p	MAXCYC
σ_h^c	$\sigma_{\alpha d}^s$	σ_{A4}	$\sigma_{\Delta\theta}$	$\alpha_{\theta\psi 2}$	$\Phi(t)$	D_R	END
σ_j^c	$\sigma_{\alpha e}^s$	σ_{A5}	$\sigma_{\Delta\theta D}$	$\alpha_{\theta\chi 2}$	γ	D_y	SPACE
$\sigma_{\alpha b}^c$	α_{bN}^s	$\sigma_{\alpha b\psi}$	$\sigma_{\Delta\phi RD}$	α_o	ρ	$R_{i,F}$	NLIST
$\sigma_{\alpha d}^c$	α_{cN}^s	$\sigma_{\alpha b\chi}$	$\sigma_{\Delta\phi pD}$	β_{co}	ϕ_{pVM}	$R_{i,s}$	INLIST
$\sigma_{\alpha h}^c$	σ_a	$\sigma_{\alpha c\psi}$	$\sigma_{\Delta\phi yD}$	β_o	ϕ_{RVM}	$R_{i,1}$	NENTRY
$\sigma_{\Delta\phi R}^c$	σ_d	$\sigma_{\alpha c\chi}$	$\sigma_{\Delta\phi tD}$	$\Delta\theta\psi_o$	ϕ_{tVM}	$R_{i,2}$	NWDS
α_{bN}^c	σ_e	$\sigma_{\alpha f2}$	$\sigma_{\Delta\phi t}$	$\Delta\theta\chi$	ϕ_{yVM}	$R_{i,G}$	LISTOB
α_{dN}^c	σ_{f1}	$\sigma_{\alpha g2}$	σ_T	$\Delta\phi p_o$	K_n^p	$T_{p_{min}}$	WRITOB
K_n^c	σ_{g1}	$\sigma_{\alpha K}$	$\alpha_{b\chi}$	$\Delta\phi t_o$	K_n^{p1}	$t_{y_{min}}$	NWORDS
K_n^{c1}	σ_h	$\sigma_{\alpha i}$	$\alpha_{b\psi}$	$\Delta\phi y_o$	A_1	$t_{R_{min}}$	
K_n^s	$\sigma_{i,F}$	$\sigma_{\alpha\psi 1}$	$\alpha_{c\chi}$	θ_p	A_2	T_{Dp}	
K_n^{s1}	$\sigma_{i,G}$	$\sigma_{\alpha\psi 2}$	α_c	θ_y	A_3	T_{Dy}	
σ_a^s	$\sigma_{i,s}$	$\sigma_{\alpha\chi 1}$	α_{f2}	θ_R	A_4	T_{D_R}	

$$X_1 = (-2 \log u_1)^{1/2} \cos (2\pi u_2)$$

$$X_2 = (-2 \log u_1)^{1/2} \sin (2\pi u_2)$$

where u_1 and u_2 are uniformly distributed pseudo-random numbers on the interval (0, 1). The u_1 and u_2 numbers are generated in subroutine RNDV. A description of subroutines RN2S and RNDV is presented in Appendixes A and B, respectively.

Table 3. Output Values

$\hat{\phi}_p$	$\hat{\alpha}_t$	χ_t
$\hat{\phi}_y$	$\hat{\beta}_t$	ψ_t
$\hat{\phi}_R$	T_t	ϕ_p
$\hat{\theta}_\psi$	t	ϕ_y
$\hat{\theta}_\chi$	α_t	ϕ_R
$\hat{\phi}_t$	β_t	

2.1.4 Subroutine OBS

Subroutine OBS (see Figure 5) contains all routines necessary to simulate the Approach Guidance System. In order to provide flexibility for possible future changes and to ease program development, OBS has been subdivided into a number of convenient subroutines. Each subroutine was designed with a specific unique function. Hence, if in the future a particular function is to be modified or changed, it can be done independently and then substituted in the program.

2.1.4.1 Subroutine LIMCYC

The spacecraft attitude is not fixed in space; it is only confined by a limit cycle. Therefore, to measure the required LOS angles, the spacecraft motion within this limit cycle must be compensated. In order to do so, subroutine LIMCYC (see Figures 6 through 9) has been specifically designed to produce a set of angles representing spacecraft body axis rotation during limit cycling. A detailed description of the information flow as presented in these figures is available in Reference 1.

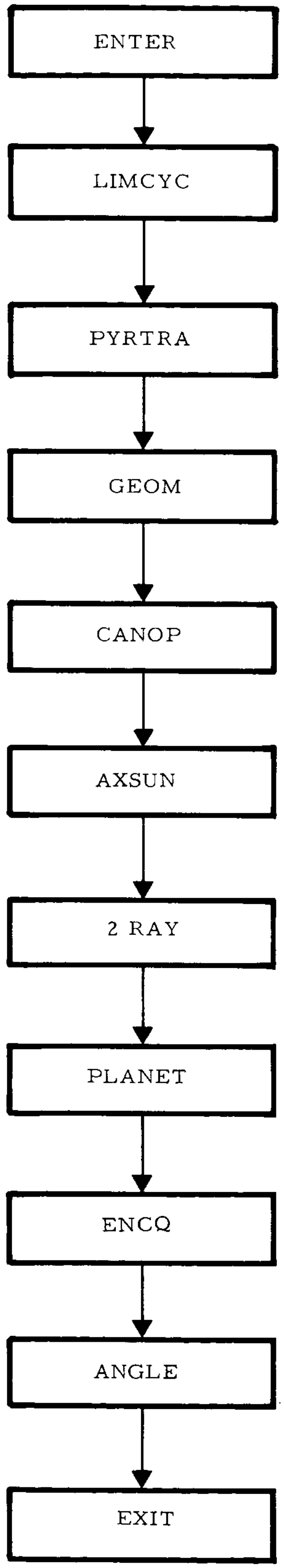


Figure 5. Subroutine OBS—Contains all Routine Required to Simulate the Approach Guidance System

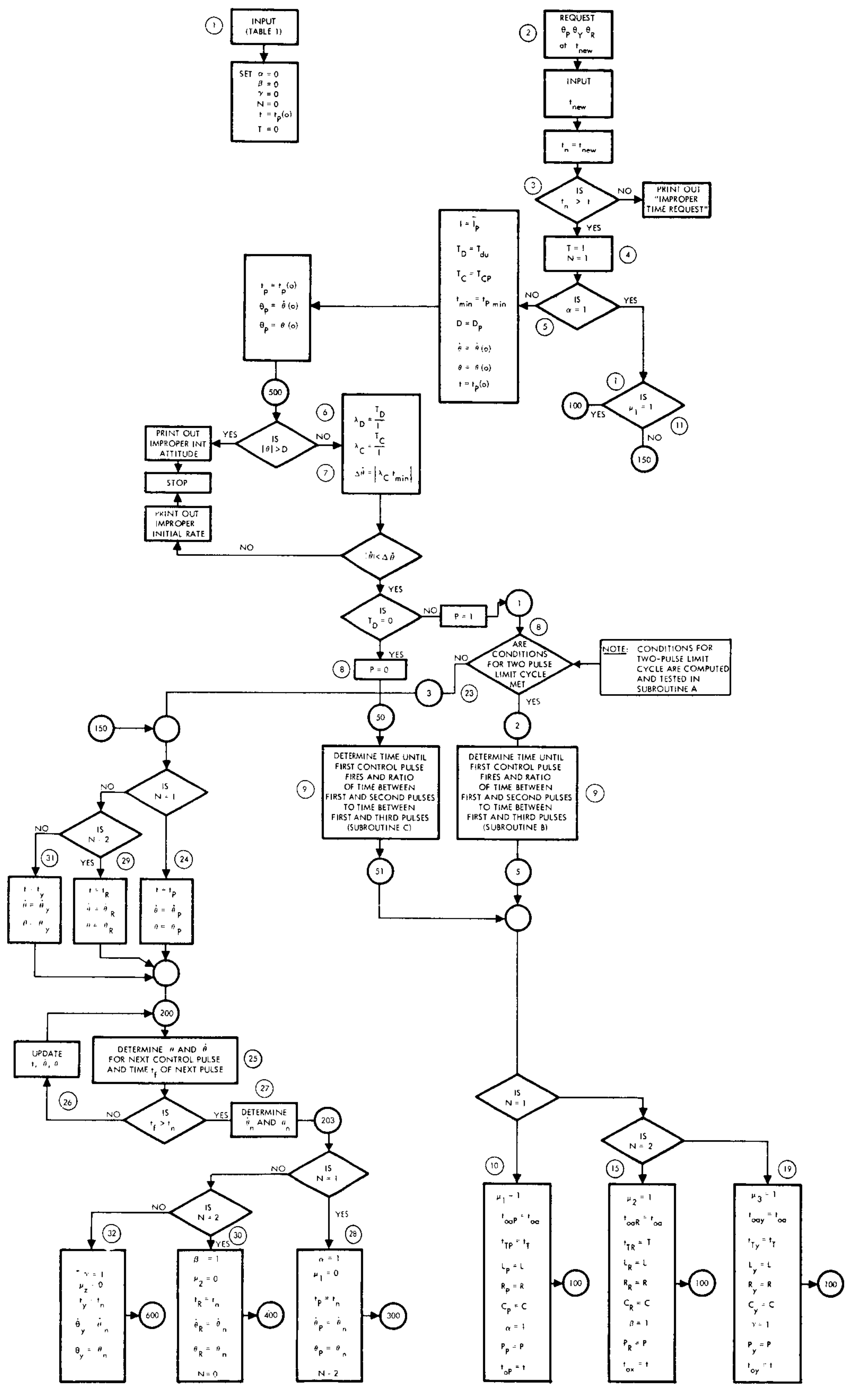


Figure 6. Limit Cycle Model Computer Flow Diagram

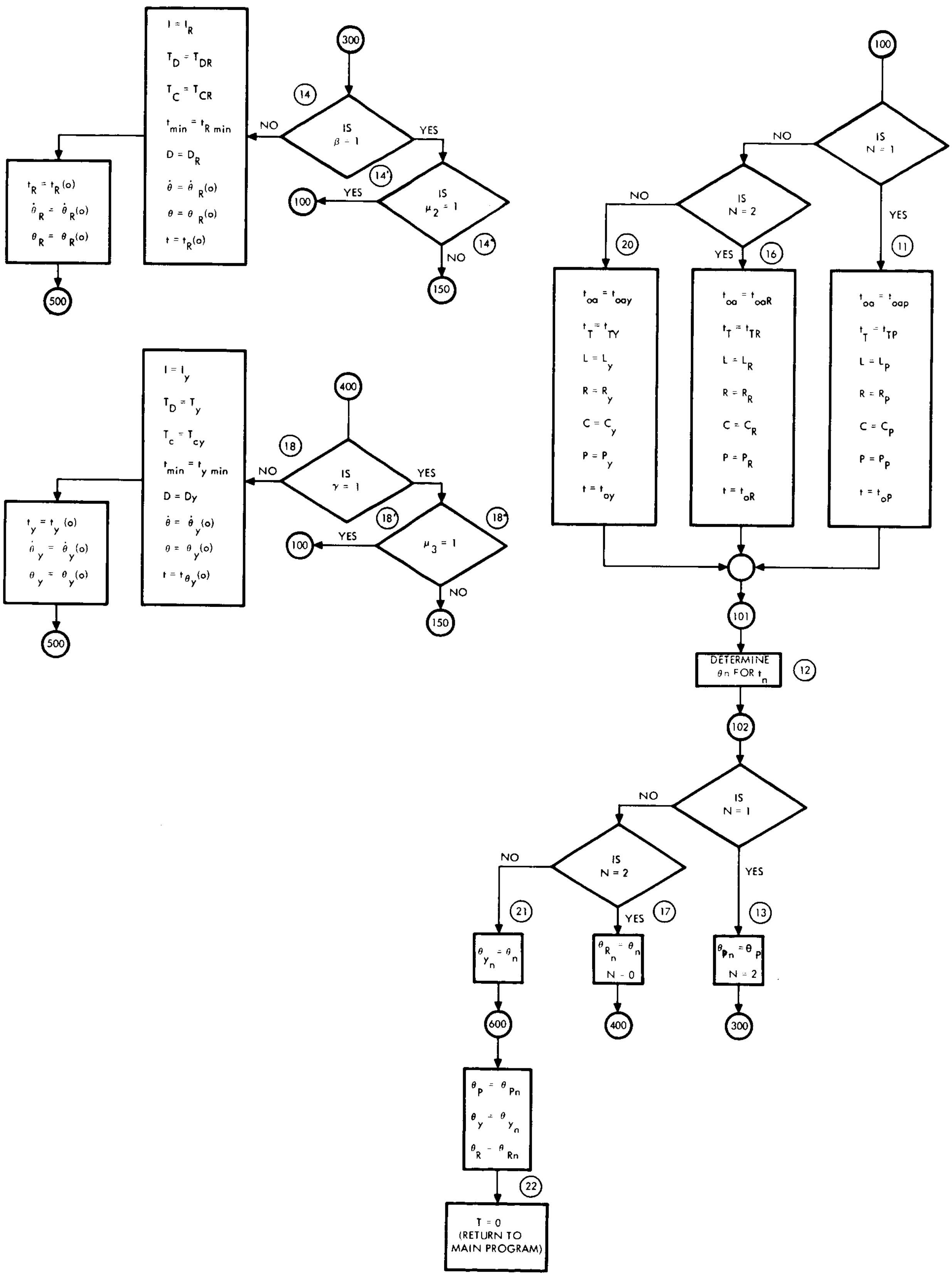


Figure 6. Limit Cycle Model Computer Flow Diagram (Concluded)

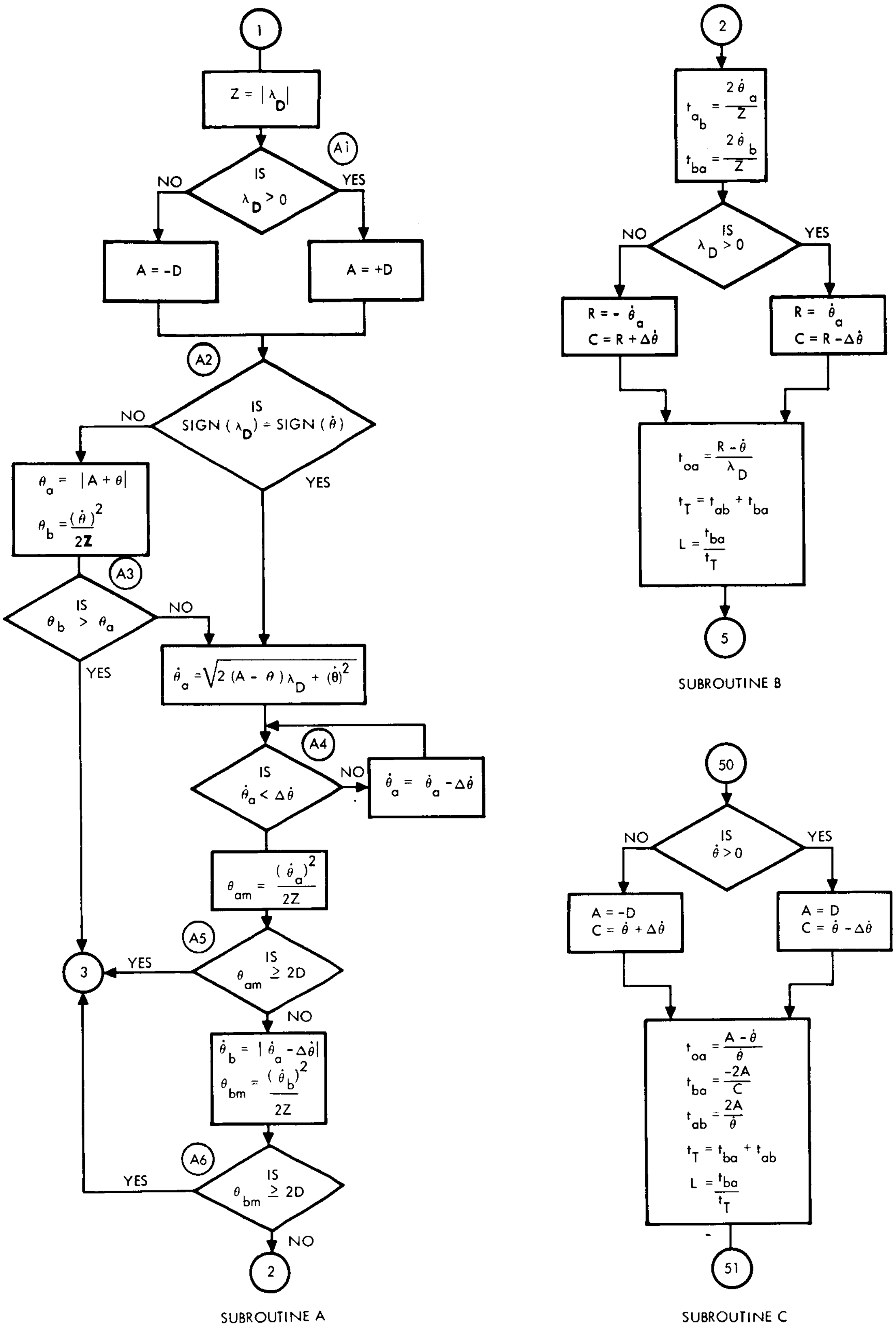


Figure 7. Two-Pulse One-Sided Disturbed Limit Cycle and Undisturbed Limit Cycle Coefficients Subroutines

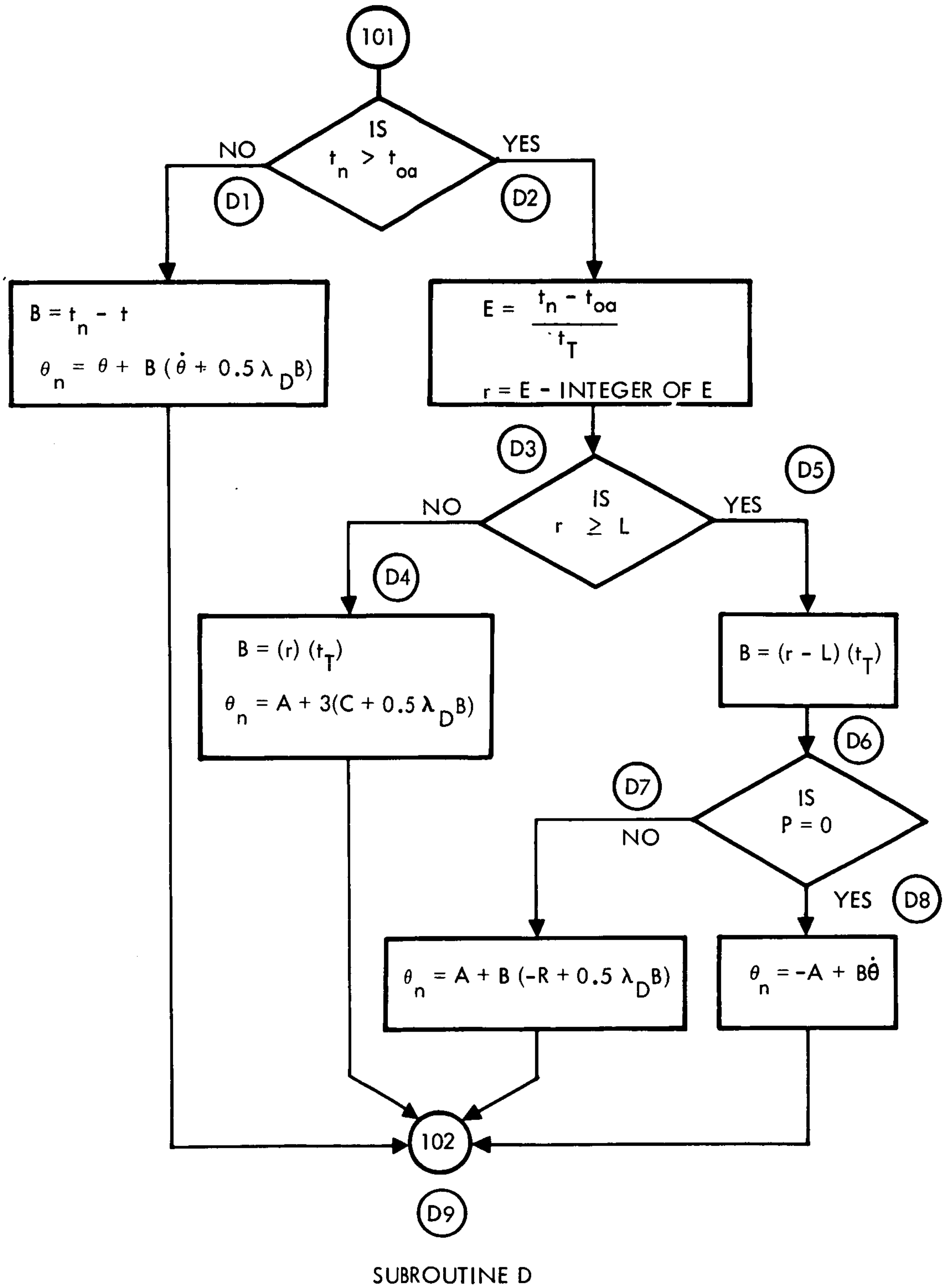


Figure 8. Disturbed Two-Pulse and Undisturbed Limit Cycle Attitude Prediction Subroutine

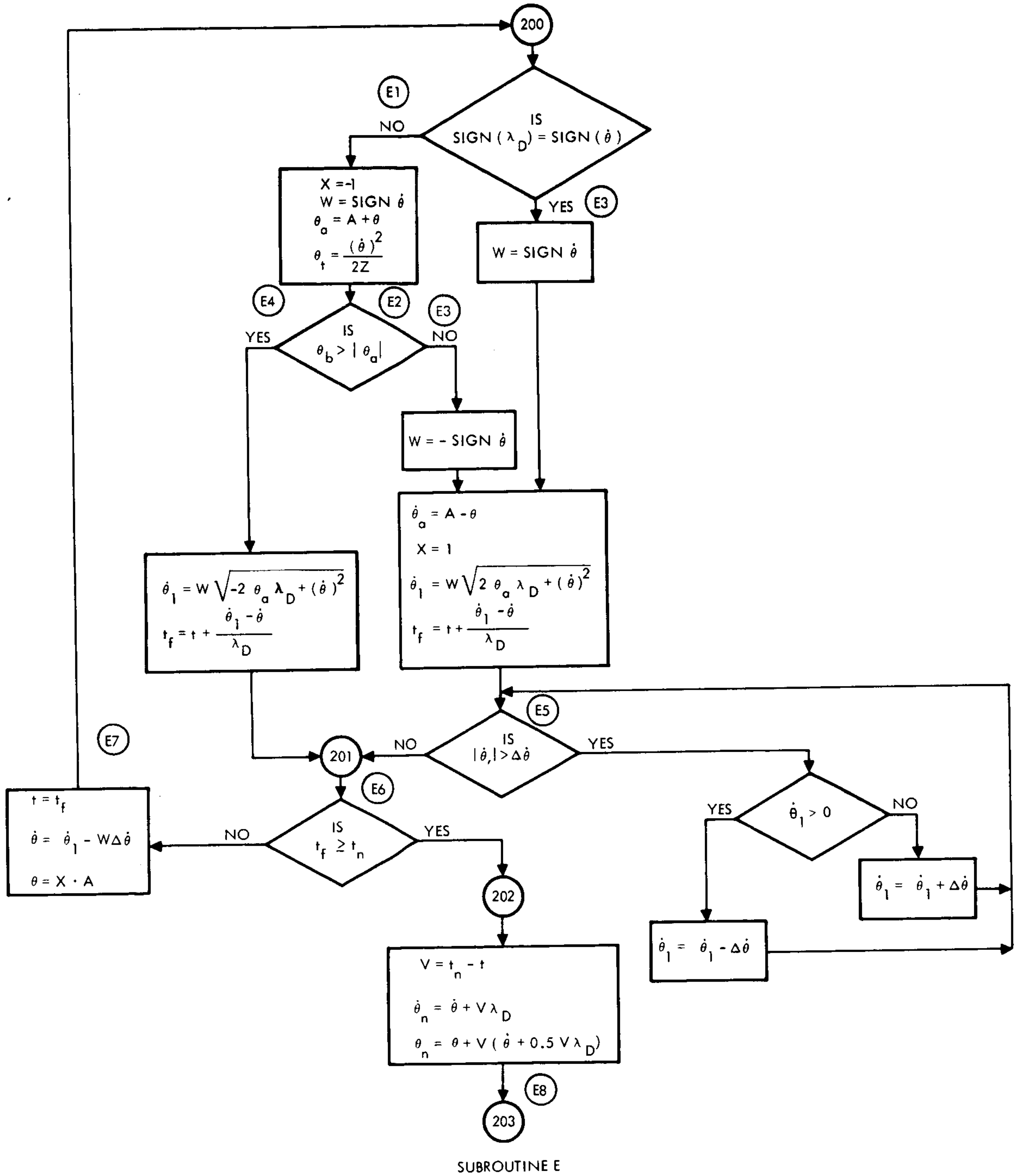


Figure 9. Multipulse Limit Cycle Attitude Prediction Subroutine

2.1.4.2 Subroutine PYRTRA

The body axis motion within the limit cycle will be recorded by the auxiliary Sun sensors and Canopus tracker. Therefore, the body axis angles must be expressed in terms of the auxiliary Sun sensors and Canopus tracker angle measurements. In order to do so, subroutine PYRTRA (see Figure 10) transforms the body axis angles computed in LIMCYC to angles measured by the auxiliary Sun sensor and Canopus tracker. The derivation of this transformation has been presented in Reference 2.

2.1.4.3 Subroutine GEOM

To simulate the planet tracker optics, the LOS angles will be expressed with respect to the optics axis. The difference between the planet tracker axis and the optics axis is the rotation of the LOS which is due to the fore prism as shown in Figure 19. The effect is to rotate the cone angle through the angle A5. The planet tracker will measure the LOS angles between the spacecraft and planet. To simulate the LOS angles, the LOS vector with respect to spacecraft coordinates will be derived from the trajectory data, orientation of the spacecraft's body axis with respect to a quasi-inertial axis, limit cycle motion, and orientation of the planet tracker with respect to the spacecraft body axis. In order to provide the LOS angles subroutine GEOM (see Figure 11) computes the planet tracker LOS cone and cross-cone angles and angle rates. The derivation of the equations is presented in Reference 3. In modeling the LOS measurements by the planet tracker there exists an error due to LOS motion within the limit cycle and the relative motion of the spacecraft with respect to the planet. Since this motion will be small for the region in which the planet tracker can effectively operate, the LOS angular rates are based on differencing the previous and current angles and dividing by the time interval.

2.1.4.4 Subroutine CANOP

Since a number of errors in the Canopus tracker, auxiliary Sun sensors, and planet tracker are due to temperature, a representative simulation of temperature is computed through the equation

ENTER WITH

$\theta_p, \theta_y, \theta_R, \gamma, \beta_c$

$$\phi_p = \frac{S_y}{S_R}, \qquad \phi_y = \frac{-S_p}{S_R},$$

$$\begin{bmatrix} S_p \\ S_y \\ S_R \end{bmatrix} = \begin{bmatrix} \theta_y - \theta_R \, \theta_p \\ -\theta_R \, \theta_y - \theta_p \\ -1 \end{bmatrix}$$

ϕ_p = pitch $\qquad \phi_y$ = yaw

$$\sin \phi_R = C_p \sin(\theta_R + \gamma) + C_y \left[\theta_p \theta_y \sin(\theta_R - \gamma) - \cos(\theta_R + \gamma)\right]$$
$$- C_R \left[\theta_y \sin(\theta_R + \gamma) + \theta_p \cos(\theta_R + \gamma)\right]$$

$$C_p = \cos\gamma \sin\beta_c, \quad C_y = \sin\gamma \sin\beta_c, \quad C_R = -\cos\beta_c$$

EXIT WITH

ϕ_p, ϕ_y, ϕ_R

Figure 10. Subroutine PYRTRA—Computes Pitch, Yaw, and Roll as Measured by the Auxiliary Sun Sensor and Canopus Tracker

Enter With

$\alpha_o, \gamma, A_5, \theta_p, \theta_y, \theta_R, \beta_o, \alpha_E^c, \alpha_E^T, \beta_n$

$$T_1^T = \begin{bmatrix} -\sin(\alpha_o - \gamma) & -\cos(\alpha_o - \gamma) & 0 \\ -\cos(\alpha_o - \gamma)\cos\beta_o & \sin(\alpha_o - \gamma)\cos\beta_o & -\sin\beta_o \\ \cos(\alpha_o - \gamma)\sin\beta_o & -\sin(\alpha_o - \gamma)\sin\beta_o & -\cos\beta_o \end{bmatrix}$$

$$T_2^T = \begin{bmatrix} 1 & \theta_R & -\theta_y \\ -\theta_R & 1 & \theta_p \\ \theta_y & -\theta_p & 1 \end{bmatrix}$$

$$T_3^T = \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ \sin\gamma & -\cos\gamma & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

$$\alpha_n = \alpha_E^T - \alpha_E^c$$

$$P = \begin{bmatrix} P_a \\ P_b \\ P_c \end{bmatrix} \qquad \begin{aligned} P_a &= \sin\beta_n \cos\alpha_n - \sin\beta_o \cos\alpha_o \\ P_b &= \sin\beta_n \sin\alpha_n - \sin\beta_o \sin\alpha_o \\ P_c &= \cos\beta_n - \cos\beta_o \end{aligned}$$

$$P_T = T_1^T \, T_2^T \, T_3^T \, P$$

$$\chi_t = \sin^{-1} P_{1T} \qquad \psi_t = \tan^{-1} \frac{-P_{2T}}{P_{3T}}$$

$$\dot{\chi}_t = \frac{\chi_t - \chi_{t-1}}{\Delta t}$$

$$\dot{\psi}_t = \frac{\psi_t - \psi_{t-1}}{\Delta t}$$

$$\Delta t = |t - (t-1)|$$

Exit With

$\chi_t, \psi_t, \dot{\chi}_t, \dot{\psi}_t$

Figure 11. Subroutine GEOM—Computes Planet Tracker Cone and Cross-Cone Angles

$$T_t = \Delta T_t + T$$

where

$$\Delta T_t = \rho \Delta T_{t-1} + RN2S(\sigma_T) \quad .$$

The equation consists of an average or nominal temperature value, T, and the variation about T. The variation about T is due to random fluctuation expressed by RN2S (σ_T) and correlation to the previous temperature measurement expressed by $\rho \Delta T_{t-1}$. Motion of one of the limit cycle angles designated as roll is provided by the Canopus tracker. Modeling of the roll angle as measured by the Canopus tracker is done in subroutine CANOP (see Figure 12). The equations representing the error sources for the Canopus tracker have been derived from and explained in Reference 1. The error sources consist of a bias which is computed in subroutine INITIAL, temperature dependent errors, and random errors. The resulting noised angle, which represents roll as measured by the Canopus tracker, is expressed in mrad.

2.1.4.5 Subroutine AXSUN

Motion of two limit cycle angles designated as pitch and yaw is provided by the auxiliary Sun sensors. Modeling of the pitch and yaw angles as measured by the auxiliary Sun sensors is done in subroutine AXSUN (see Figure 13). The equations representing the error sources have been derived and explained in Reference 1. The error sources consist of a bias which is computed in subroutine INITIAL, temperature dependent errors, and random errors. The resulting noised angles which represent pitch and yaw as measured by the auxiliary Sun sensors are expressed in mrad.

2.1.4.6 Subroutine 2RAY

Subroutine 2RAY (see Figures 14 through 17) computes planet tracker wedge angles which represent the LOS angles. The planet tracker optical gimbal configuration is presented in Figure 19. Subroutine AGOPT traces the LOS ray through the optics. The X-axis and Y-axis wedges are rotated until the incoming ray is parallel to the planet tracker null axis. Subroutine BEND traces the ray through a reflection surface while subroutine BOUNCE

Enter With

$\epsilon_{cb}, \alpha_b^c, \alpha_T^c, \sigma_j^c, \phi_R, \beta_{co}, \beta_c, \sigma_T, T, \Delta T_{t-1}, \rho,$

↓

$$T_t = \Delta T_t + T$$
$$\Delta T_t = \left[\rho \Delta T_{t-1} + \mathrm{RN2S}\,(\sigma_T)\right]$$

↓

$$\Delta\beta = \beta_{co} - \beta_c$$
$$\epsilon_B^c = \alpha_b^c \Delta\beta \qquad \epsilon_j = \mathrm{RN2S}\ \sigma_j^c$$
$$\epsilon_T^c = \alpha_T^c\ T_t$$

↓

$$\hat{\phi}_R = \phi_R + \epsilon_{cb} + \epsilon_b^c + \epsilon_T^c + \epsilon_j$$

↓

Exit With

$T_t, \sigma_T, \hat{\phi}_R, \Delta T_t$

Figure 12. Subroutine CANOP — Computes Roll Angle as Measured by the Canopus Tracker

ENTER WITH

$\alpha_T^s, \epsilon_{Rdp}^s, \epsilon_{ady}^s, T_t, \phi_p, \phi_y$

$$\epsilon_{By}^s = \epsilon_{Bp}^s = \alpha_T^s \, T_t \qquad \epsilon_{fp} = \text{RN2S} \, \sigma_f^s$$

$$\epsilon_{fy} = \text{RN2S} \, \sigma_f^s$$

$$\hat{\phi}_p = \phi_p + \epsilon_{adp}^s + \epsilon_{Bp}^s + \epsilon_{fp}$$

$$\hat{\phi}_y = \phi_y + \epsilon_{ady}^s + \epsilon_{By} + \epsilon_{fy}$$

EXIT WITH

$\hat{\phi}_p, \hat{\phi}_y$

Figure 13. Subroutine AXSUN—Computes Pitch and Yaw as Measured by the Auxiliary Sun Sensors

Enter With

$\psi_m, \chi_m, \chi_t, \psi_t, \theta_{\chi_{t-1}}, \theta_{\psi_{t-1}}, \sigma_{\alpha\psi}, \alpha_{b\chi}, \alpha_{b\psi}, \chi_t, \psi_t$

↓

$$\chi_t = \chi_t + \alpha_{b\psi}\, \psi_t\, \frac{\alpha^2_{b\chi}}{2}\, \chi_t + \alpha_{c\psi}\, \psi_{\bar{t}}\, \frac{\alpha^2_{c\chi}}{2} \chi_t + \mathrm{RN2S}\ \sigma_a$$

$$\chi_t = \psi_{\bar{t}}\, \alpha_{b\chi}\, \chi_t - \frac{\alpha^2_{b\psi}}{2}\, \psi_t - \alpha_{c\chi}\, \chi_{\bar{t}}\, \frac{\alpha^2_{c\psi}}{2} \psi_t + \mathrm{RN2S}\ \sigma_a$$

↓

Compute Los Vector V

$V_1 = \mathrm{Sin}\ \chi_t \qquad V_2 = -\mathrm{Cos}\ \chi_t\ \mathrm{Sin}\ \psi_t \qquad V_3 = \mathrm{Cos}\ \chi_t\ \mathrm{Cos}\ \psi_t$

↓

AGOUT

↓

Exit With

$\chi_t, \psi_t, \theta_{\chi t}, \theta_{\psi t}$

Figure 14. Subroutine 2RAY—Traces the Line-of-Sight Ray Through the Planet Tracker Optics

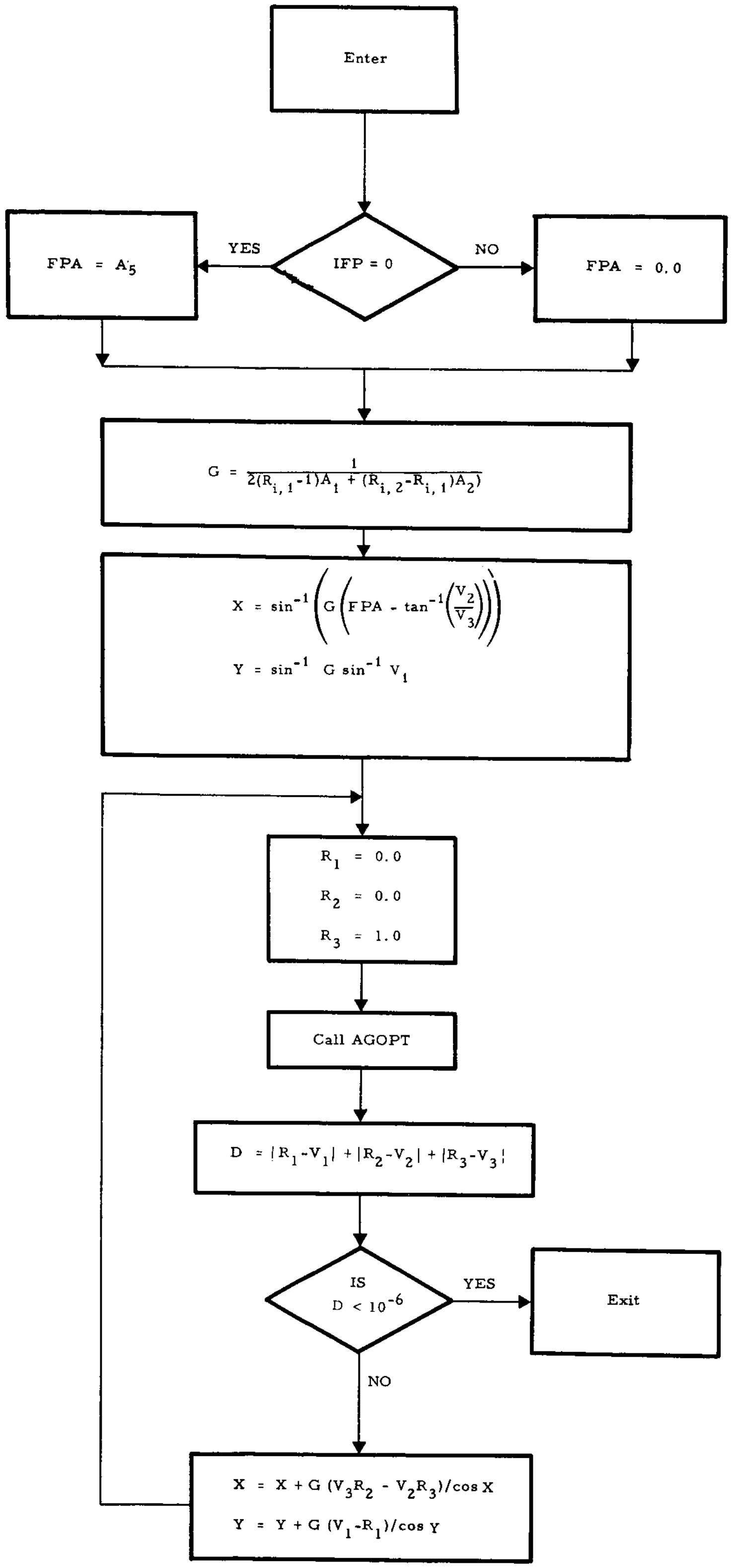


Figure 15. Subroutine AGOUT—Computes the Line-of-Sight Angles as Measured by the Planet Tracker Wedges

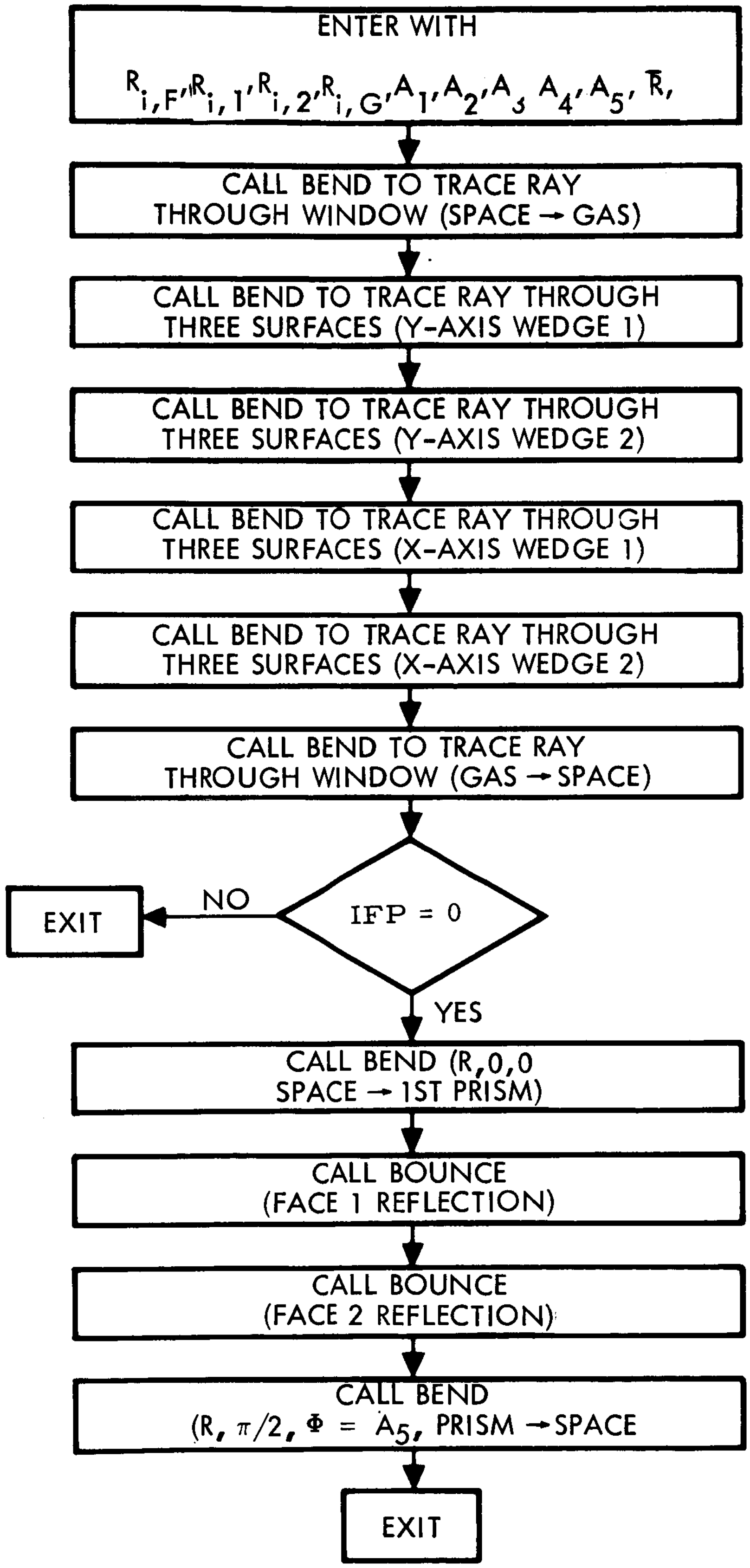


Figure 16. Subroutine AGOPT—Traces the Line-of-Sight Ray Through the Planet Tracker Optics

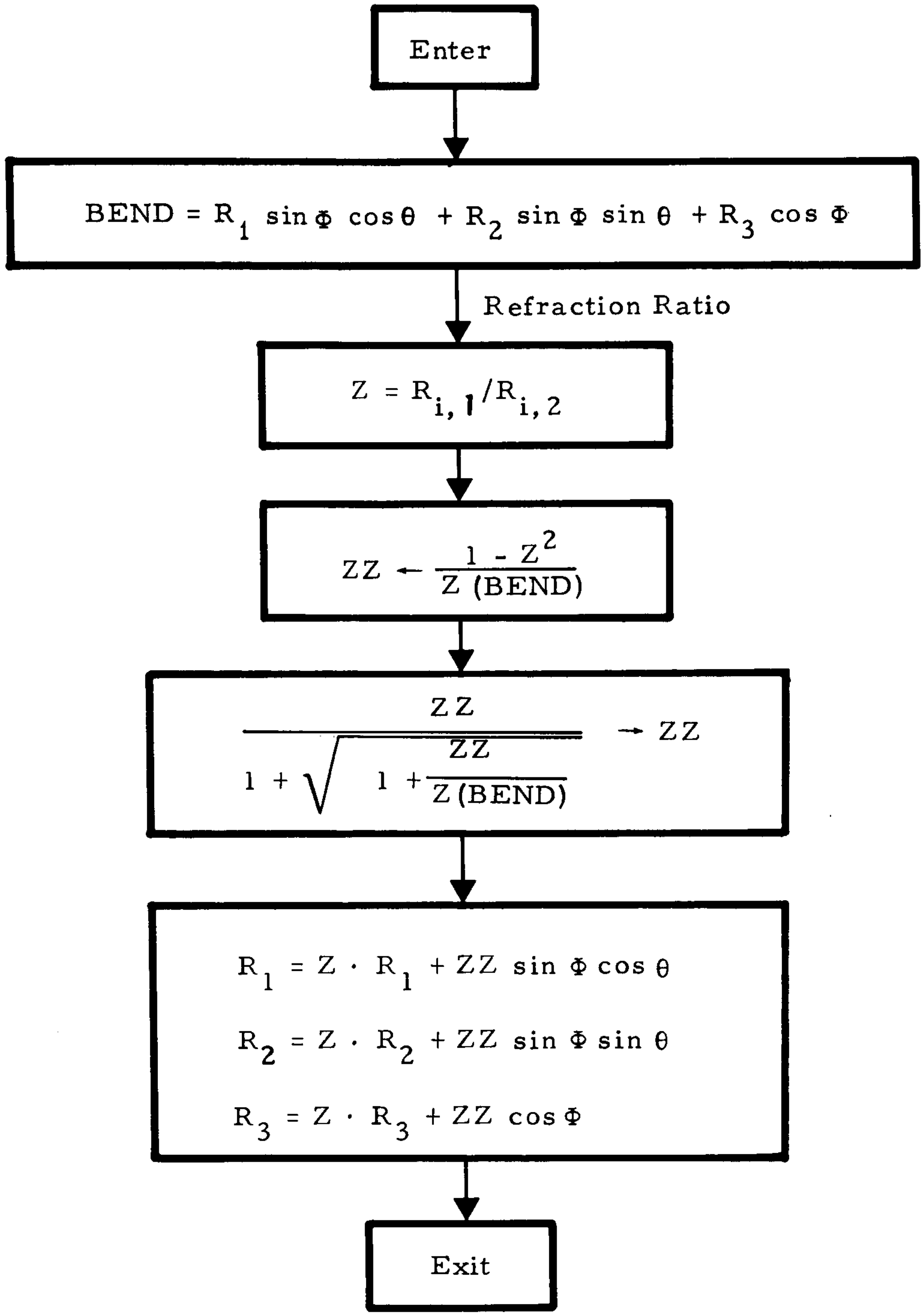


Figure 17. Subroutine BEND—Traces the Line-of-Sight Ray Through Refraction Optics

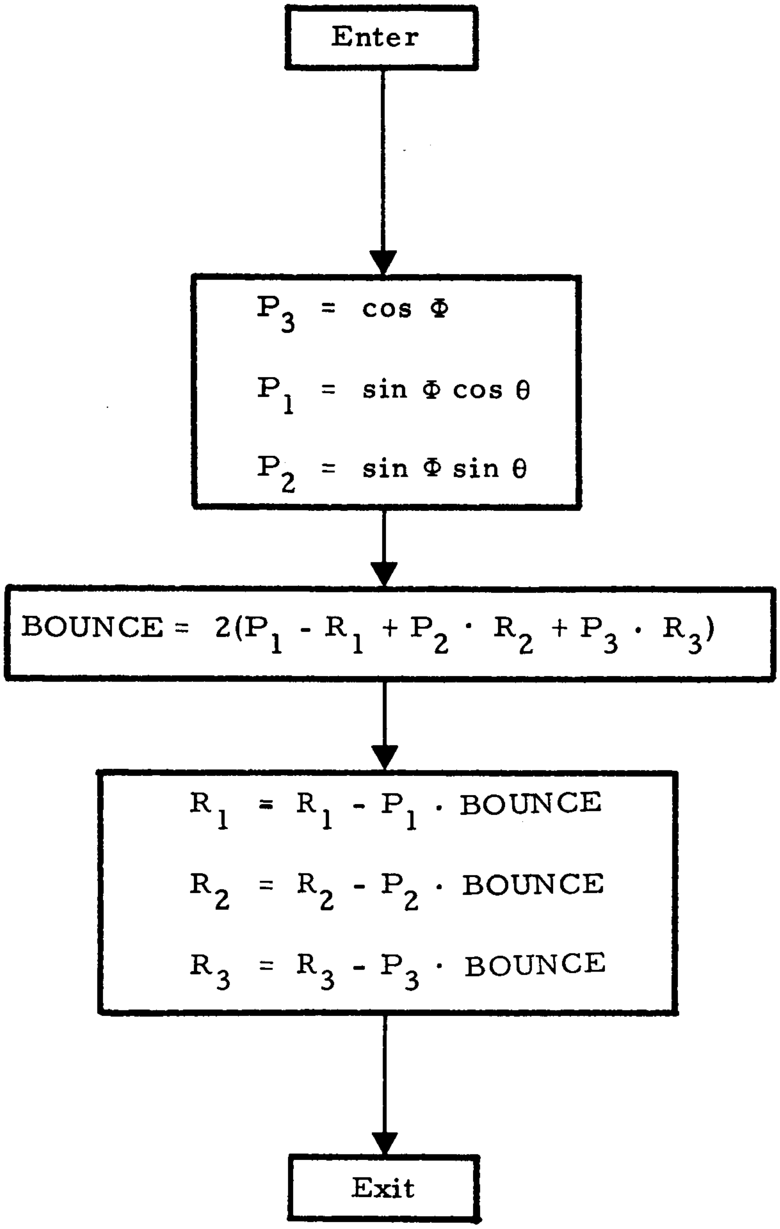
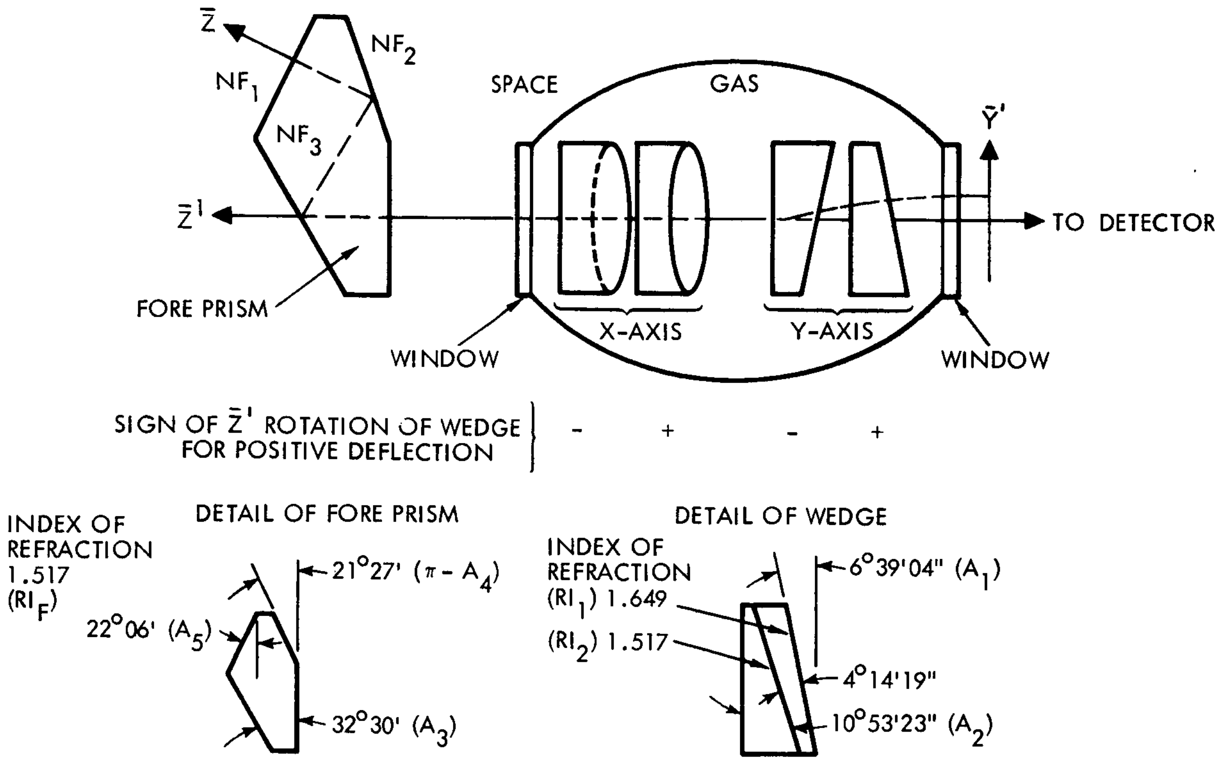


Figure 18. Subroutine BOUNCE—Traces the Line-of-Sight Ray Through a Reflection Surface



OPTICAL SURFACES FOR REFRACTION OR REFLECTION ARE DEFINED BY THEIR NORMALS, NOMINALLY DEFINED IN GENERAL DIRECTION OF A RAY LEAVING THE TRACKER. THE NORMALS ARE DEFINED IN THE FOLLOWING POLAR COORDINATES, (θ, ϕ):

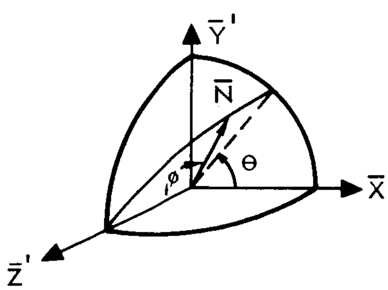


Figure 19. Planet Tracker Optical Gimbal Configuration

traces the ray through a refraction surface. All errors inherent with the planet tracker optics system as sketched in Figure 19 are included. The errors have been identified and described in Reference 1. Modeling rotation of the optical wedges is done through the use of subroutine AGOUT (see Figure 15). Given the LOS vector, a ray is traced through the optics, the resulting LOS vector is compared with the given LOS vector, and the routine is exited when these match up within a specified tolerance.

2.1.4.7 Subroutine PLANET

The measurements of the LOS angles that are expressed as cone and cross-cone angles by the planet tracker are obtained by rotating the optical wedges modeled in subroutine 2RAY. The electronics of the servomechanism loop and the electronics that lock on the planet, maintain lock on the planet, and establish the center of the planet are modeled in subroutine PLANET (see Figure 20) which computes planet diameter and planet tracker cone and cross-cone wedge angles. The equations representing the error sources have been derived and explained in Reference 1. The error sources consist of bias, temperature dependent errors, and random errors. These errors are added to the planet tracker angles computed in 2RAY. Having modeled the angle measurements of the Canopus tracker, auxiliary Sun sensors, and planet tracker, the modeling of this final phase is done in subroutine ENCQ and ANGLE. This consists of quantizing the measurements, telemetering them to earth, and deriving the cone and clock angles that will constitute the observables to be used in orbit determination of the spacecraft.

2.1.4.8 Subroutine ENCQ

The quantization modeling of the Canopus tracker roll angle, auxiliary Sun sensors pitch and yaw angles, and the planet tracker cone, cross-cone, and planet diameter angles is done in subroutine ENCQ (see Figure 21). The formulation is based on equations and error sources presented in Reference 1. To avoid ambiguity when the encoded value is zero, the planet tracker cone and cross-cone angles have been biased so that -60° (-1.745 rad) is the zero digital state. The Canopus tracker roll angle and auxiliary Sun sensors pitch and yaw angles have been biased such that -1.0 volt is the zero digital state.

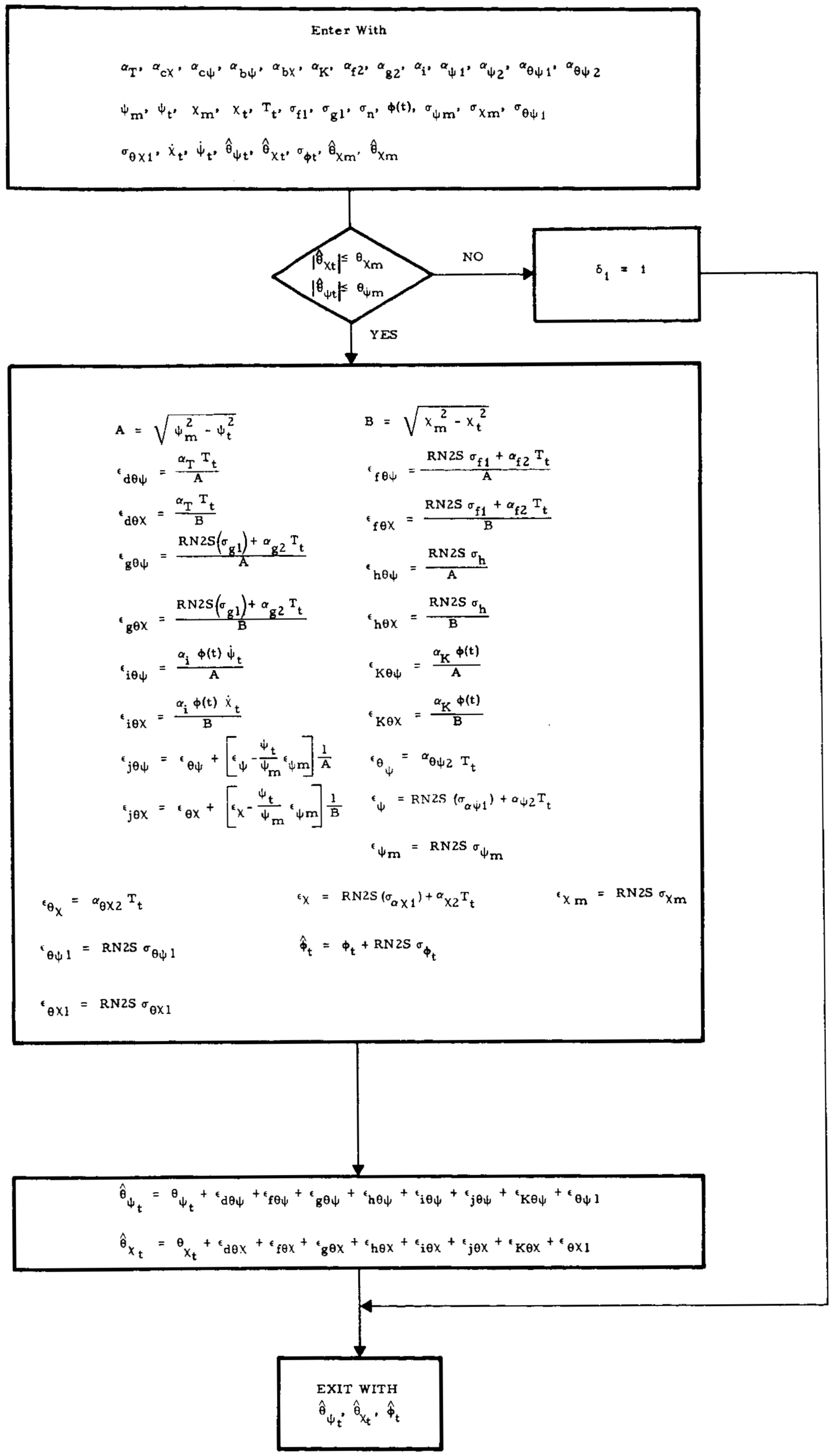


Figure 20. Subroutine PLANET — Computes Noised Planet Tracker Cone and Cross-Cone Angles

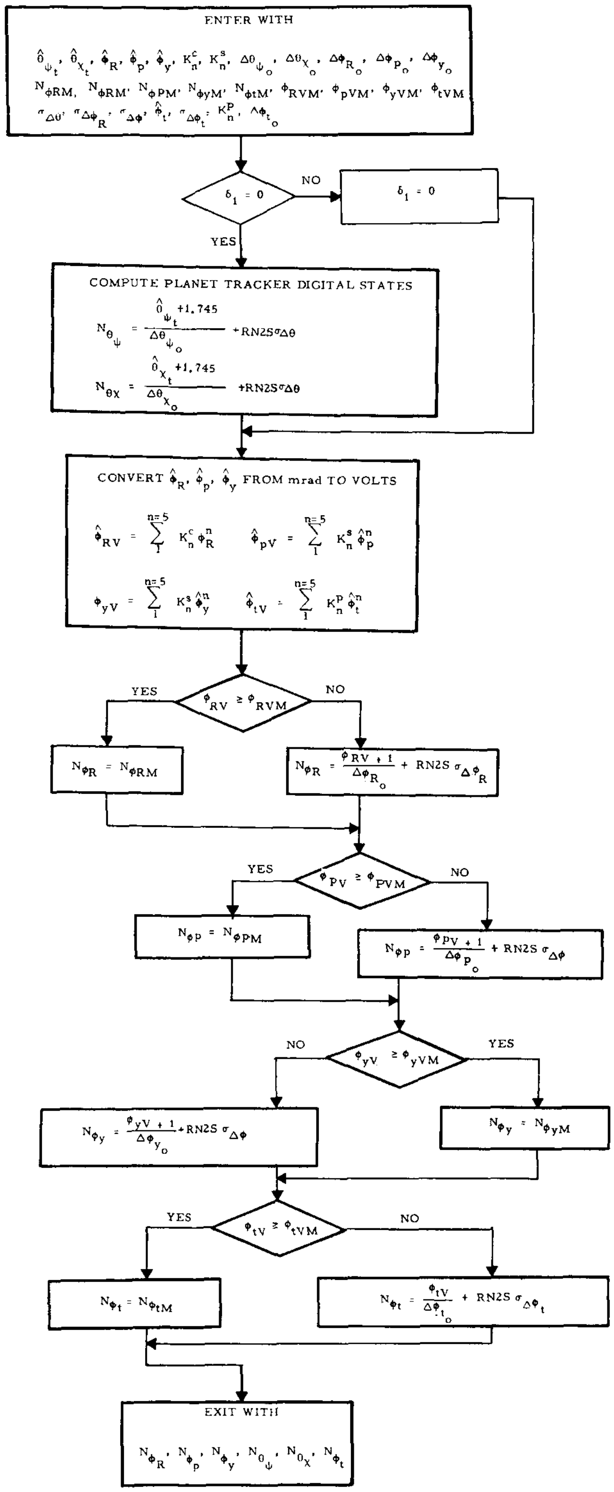


Figure 21. Subroutine ENCQ—Quantizes the Observation Data Taken by The Auxiliary Sun Sensors, Canopus Tracker, and Planet Tracker

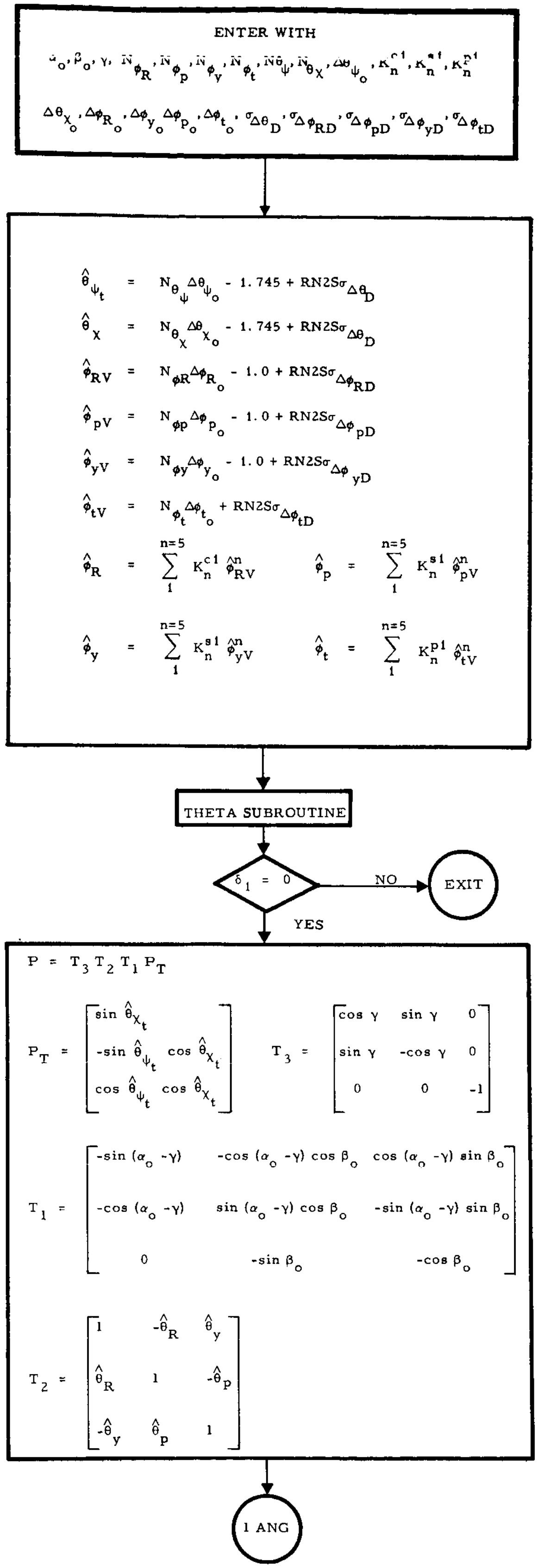


Figure 22. Subroutine ANGLE—Computes Cone, Clock, Pitch, Yaw and Roll as Derived from Measurements Taken by the Planet Tracker, Auxiliary Sun Sensors and Canopus Tracker

1 ANG

$$P = \begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix} \qquad \begin{aligned} P_a &= P_1 + \sin\beta_o \cos\alpha_o \\ P_b &= P_2 + \sin\beta_o \sin\alpha_o \\ P_c &= P_3 + \cos\beta_o \end{aligned}$$

$$\hat{\alpha}_t = \mathrm{TAN}^{-1}\left[\frac{P_b}{P_a}\right] \qquad 0 \leq \hat{\alpha}_t < 360°$$

$$\hat{\beta}_t = \cos^{-1} P_c \qquad 0 \leq \hat{\beta}_t \; 180°$$

EXIT WITH

$\hat{\alpha}_t$, $\hat{\beta}_t$, $\hat{\theta}_p$, $\hat{\theta}_y$, $\hat{\theta}_R$

Figure 22. Subroutine ANGLE (Concluded)

2.1.4.9 Subroutine ANGLE

Subroutine ANGLE, Figure 22, computes cone, clock, and body axis angles based on Canopus tracker, auxiliary Sun sensors, and planet tracker measurements. Hence the decoding simulation is contained in this subroute. The transformation from Canopus tracker and auxiliary Sun measurements of roll, pitch, and yaw (ϕ_R, ϕ_p, ϕ_y) to body axis (θ_R, θ_p, θ_y) is based on the derivation presented in Reference 2. The transformation is contained in subroutine THETA (Figure 23).

ENTER WITH

$\hat{\phi}_p$, $\hat{\phi}_y$, $\hat{\phi}_R$, α_o, β_c

↓

$$\hat{\theta}_{R_o} = \frac{\hat{\phi}_R - \cos\beta_c\,(\hat{\phi}_p \cos\alpha_o + \hat{\phi}_y \sin\alpha_o)}{\sin\beta_c}$$

$$\hat{\theta}_p = \hat{\phi}_p - \hat{\phi}_y\,\theta_{R_o}$$

$$\hat{\theta}_y = \hat{\phi}_y - \hat{\phi}_p\,\theta_{R_o}$$

$$\hat{\theta}_R = \frac{\hat{\phi}_R - \cos\beta_c\,(\hat{\theta}_p \cos\alpha_o + \hat{\theta}_y \sin\alpha_o) - C_y\,\hat{\theta}_p\,\hat{\theta}_y \sin\alpha_o}{\sin\beta_c - \cos\beta_c\,(\hat{\theta}_p \sin\alpha - \hat{\theta}_y \cos\alpha_o)}$$

$$C_y = \sin\alpha_o \sin\beta_c$$

↓

EXIT WITH

$\hat{\theta}_p$, $\hat{\theta}_y$, $\hat{\theta}_R$

Figure 23. Subroutine THETA — Computes Body Axis Motion Within the Limit Cycle Which is Derived from Auxiliary Sun Sensors and Canopus Tracker Measurements

3. NEW TECHNOLOGY

No new technology was conceived or adapted for usage during the development of the Prototype Computer Program.

APPENDIX A

G5, IBMAP SUBROUTINE, RW RN2S (REVISED APRIL 15, 1963)

Identification

RW RN2S - Normal Random Number Generator
7090 - IBMAP
Harley R. Stafford,* March 23, 1961
Space Technology Laboratories, Inc.

Purpose

To generate independent random numbers, each normally distributed with mean zero and standard deviation unity, in floating point form.

Restrictions

Cycles every 2^{33} numbers.

Method

This subroutine uses CS RDM1 Uniformly Distributed Pseudo-random Numbers to obtain uniformly distributed random numbers between zero and one, and transforms them using the equations

$$X_1 = (-2 \log_e u_1)^{1/2} \operatorname{Cos} (2\pi u_2)$$

$$X_2 = (-2 \log_e u_1)^{1/2} \operatorname{Sin} (2\pi u_2)$$

where u_1 and u_2 are two random numbers obtained from RDM1, and where X_1 and X_2 are two independent normally distributed random numbers with mean zero and standard deviation unity. It is noted that these equations involve pairs of random numbers, although just one number is produced upon each entry to the subroutine.

Usage

Calling Sequence: CALL RN2S (A, L)

where A is the location of the resulting floating-point random number, and

L is the location of a twelve digit octal number which should be saved in octal form from one machine run to the next and restored in octal

* Modified for IBMAP by John Alexander, Space Technologies Laboratories, Inc.

form at the beginning of the subsequent machine run in order to continue the number generating sequence. To start the sequence, a fixed point octal one (1) at a B of 35 should be loaded into L.

Coding Information

Timing: 668 machine cycles per two random numbers.

Space Requirements

280 cells of program and constants.

Number of Pages

Write-up	2
Listing	6
Total	8

APPENDIX B

G5, CS RDM1 (*REVISED JULY 30, 1959)

Identification

CS RDM1 Uniformly Distributed Pseudo-random Numbers
704 (SAP) and/or 709 (SCAT)
C. Swift, October 1956
Convair, San Diego

Purpose

To generate a uniformly distributed pseudo-random number between zero and one.

Restrictions

Cycles after 2^{33} numbers.

Method

A new random number y_i (in fixed point) is generated from the previously generated number y_{i-1} by taking the least significant portion of the fixed point product $5^{15}\ y_{i-1}$. This sequence has a period of 2^{33} or about $10^{9.9}$. The left most 27 bits of the 35 bit result are converted to a normalized floating point number between 2^{-28} and one.

Reference: National Bureau of Standards Report 3370, Generation and Testing of Pseudo-random Numbers by Olga Taussky and John Todd.

Usage

Calling Sequence: TSX RDM, 4

The next floating point pseudo-random number in the sequence is left in the accumulator.

Coding Information

1. No usable constants.
2. Requires 10 storage locations. Does not use COMMON.
3. Time: 480 microseconds.
4. The fixed point random number (a positive integer scaled at 35) is left in RDM+9. The programmer may restart the sequence from one machine run to the next by saving C (RDM+9) before saving C (RDM+9) at the end of a machine run and restoring C (RDM+9) before entering the subroutine the first time on a subsequent machine run.

* Calling sequence changed. Was RDM1

Checkout

Used in various problems. Statistical checks made here and elsewhere on method.

Number of pages

Write-up	1
Listing	1
Total	2

REFERENCES

1. Goldman, J. J., "Approach Guidance System Mathematical Error Model," Technical Report 09059-6001-R081, TRW Systems, 1 September 1967.

2. Duxbury, T. C., "Determining the Spacecraft's Celestial Orientation from Sun Sensors and Canopus Tracker Measurements," JPL Guidance and Control Technical Memo No. 343-94, 16 May 1967.

3. Barone, L. J., "Optical Approach Measurement System Observables Definition and Equations for DPODP," JPL Guidance and Control Technical Memo No. 343-91, 18 November 1966.

4. Breckenridge, W. G., "Program for Encoder Angle Grids to A/G Output Line-of-Sight," JPL Unpublished Guidance and Control Technical Memo.